The Impacts of the Extractives on Biodiversity, Ecosystem Services and Conservation Prioritisation
Management Options in the Andes and Western Amazon

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by

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"From Nature's chain, whatever link you strike,
Tenth, or ten thousandth, breaks the chain alike."

Alexander Pope, Essay on Man, written in 1732

ABSTRACT

Extractive operations in the Andes and Western Amazon overlap with important biodiversity sites and areas of high ecosystem services provision. On one hand, the governments of Colombia, Ecuador and Peru have been increasingly developing and exploiting oil and gas, and mining resources due to the high revenues and important contribution to their national economies. On the other, conservation priorities at regional- and global-scale recognise the importance of preserving these priority sites for their biodiversity value and ecosystem services relevancy. The work contained in this thesis identifies ecosystem services that are at risk due to the extractive activities and proposes novel ways on how to evaluate these risks and prioritise conservation, ultimately contributing towards a more sustainable development of extractives in the region.

As part of the research, the use of GIS techniques and modelling tools was tailored to suit the complexities of the diverse combination of variables. Datasets of mining for minerals and precious metals concessions, as well as oil and gas concessions are confronted with biodiversity and ecosystem services parameters, in order to obtain an appropriate understanding of current impacts extent and their implications. Around three quarters of the Amazon in Ecuador and Peru is covered by oil and gas concessions, whilst mining concessions are predominant in the Andes slopes. These extractive concessions overlap with protected areas and conservation priority sites. Some areas of pristine rainforest in Peru (Pacaya Samiria National Reserve) and Ecuador (Yasuni National Park) were consistently identified as high providers of carbon services, water provision and natural hazard mitigation services, as well as being home to high numbers of species of several taxonomic groups, many of them endemic to the region. This is the conflictive baseline situation of extractives and conservation priorities in the region.

Modelling tools were used to establish this baseline, and from then they were applied in two ways: *a)* to evaluate different strategies for conservation prioritisation, and *b)* to create potential but realistic scenarios of future extractive development in the region. Conservation prioritisation strategies that include considerations of multiple ecosystem services, threatened biodiversity, current pressure and future threats were set to detect the topmost sites recommended for conservation. This prioritisation assessment utilised the threshold of 17% of the top areas, to resemble the Aichi target 11 for 2020. Most of the identified priority areas (77%) are already covered by current protected areas system, which helps

strengthening the case to protect them, but a considerable portion (31%) is also overlapped by extractive concessions, which pose a threat to their conservation in the long term.

The modelled development scenarios for extractives showed that mining operations in the Andes would cause comparatively lesser impact extent in area, but highly localised impacts that could potentially harm the means of subsistence of local populations. On the other hand, modelled oil and gas extraction in the lowlands of the Amazon is larger in extent, but may cause harm to relatively less people. Nevertheless, the pristine rainforests that would be affected hold immense value of globally- (e.g. carbon) and locally-relevant (e.g. water provision) ecosystem services and constitute the habitat of unique high levels of biodiversity. Furthermore, the spatial results show how potential residuals of all modelled extractive operations could cause off-site impacts that travel far downstream the waterways even crossing international borders.

Management options for extractive development should try to find a middle ground that recognises the topmost priority areas for conservation as no-go zones for extraction, but leaves other areas of comparatively less importance to be developed under strict environmental policy control that minimises the impacts on biodiversity and ecosystem services we all rely on.

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Thank you all for your encouragement!

ABBREVIATIONS

ANH	*Agencia Nacional de Hidrocarburos*, Hydrocarbons National Agency, Colombia
ARCOM	*Agencia de Regulacion y Control Minero*, Mining Control and Regulation Agency, Ecuador
ARIES	Artificial Intelligence for Ecosystem Services
BINGOs	big international Non-Governmental Organisations
CBD	Convention on Biological Diversity
CN	Costing Nature
COP	Conference of the Parties
DEM	Digital Elevation Model
EPA	United States Environmental Protection Agency
GIS	Geographical Information System
HF	Human Footprint on Water
HydroSHEDS	Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales
INIGEMM	*Instituto Geologico Minero y Metalurgico*, National Institute of Metallurgical, Geological and Mining Research, Ecuador
INGEMMET	*Instituto Geologico Minero y Metalurgico*, Geological, Mining and Metallurgical Institute of Peru
INGEOMINAS	Colombian Geological Service
InVEST	Integrated Valuation of Environmental Services and Trade-offs
IIRSA	Initiative for the Integration of Regional Infrastructure in South America
LDD	Local Drain Direction
MA	Millennium Ecosystem Assessment
MCA	Multi-Criteria Analysis
OCP	*Oleoducto de Crudos Pesados*, Ecuadorian Heavy-Oil Pipeline
PSS	Policy Support System

RAISG	*Red Amazónica de Información Socioambiental Georreferenciada*, Amazonian Network of Georeferenced Socio-environmental Information
SimTerra	Global database of environmental variables underpinning the Policy Support Systems
SOTE	*Sistema de Oleoducto Trans-Ecuatoriano*, Trans-Ecuadorian Oil Pipeline System
SRTM	Shuttle Radio Topography Mission
TEEB	The Economics of Ecosystems and Biodiversity
WA	Western Amazon
WW	WaterWorld

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CHAPTER 1:

INTRODUCTION

1.1 OVERVIEW

This thesis is the result of the research on the impacts of extractive industries on the ecosystems services, biodiversity and their implications on conservation priorities of the Western Amazon. By 'extractives', I include the historical and major extractive industries in the region, namely oil and gas, as well as mining for minerals and precious metals. This chapter starts with a brief introduction to the topic; then identifies the research problem, aim, and objectives of the thesis; and ends with a short description of the following chapters in order to show the sequential structure and to place them together as a whole.

1.2 WHY IS THE WESTERN AMAZON RELEVANT?

Extractive industries, in particular mining for minerals, precious metals, and oil and gas, have expanded all around the world, over land and sea, with serious risks for biodiversity conservation, ecosystem services preservation and affecting indigenous and rural populations' livelihood (Cuba et al., 2014; Kennedy & Cheong, 2013; O'Faircheallaigh, 2013). In effect, extractive activities are located in all types of ecosystems, including threatened and delicate tropical rainforests, such as those found in the Amazon region of Peru, Ecuador and Colombia (i.e. the Western Amazon). This area has been widely recognised for its unparalleled species richness and endemism, accounting for approximately 4,000 species of vertebrates, almost half of them endemic, and more than 30,000 endemic species of plants, as well as considered a refuge of biodiversity due to its geological history (Azevedo-Ramos & Galatti, 2002; Bass et al., 2010; Beck et al., 2013; Colinvaux & De Oliveira, 2001; Hamilton et al., 2007; Latrubesse et al., 2010, Moura et al., 2013; Myers et al., 2000; Salo, 1987; Tole, 2006). Even more, an approximate 20% of the Western Amazon territories are under some type of protection (RAISG, 2012a). However, similar geological factors make the Western Amazon rich in oil and mineral reserves; hence, the central governments of Colombia, Ecuador and Peru have been increasingly developing and exploiting oil and gas reserves in these remote areas, with minimum concern about the potential impact on biodiversity and loss of ecosystem services (Finer et al., 2008; Martinez-Alier, 2011; Gavalda, 2007; Mayorga Alva, 2007). Mining for precious metals has had a long history and impact of more than a century, and up until recently the toll it has taken on the ecosystem services had not even been considered (Adler Miserendino et al., 2013; Bebbington et al., 2008; Veiga and Meech, 1995).

Ecosystem services are understood as the benefits that people receive from ecosystems. These services are classified as provisioning, regulating, cultural and supporting services depending on the type of benefit they provide (MA, 2003; TEEB, 2013). Furthermore, an ecosystem is defined as a functional unit formed by the living organisms and the environment that hosts them (MA, 2003). The ecosystems in the Western Amazon are providing services at global scale, in terms of carbon storage and sequestration, as well as local benefits, such as water provision, and mitigation of natural hazards; even more they contain a high density of biodiversity of all taxa (Bremer et al., 2014; Cuba et al., 2014, Kauffman, 2014; Rodriguez et al., 2015). The maintenance of these services are of particular importance for rural population and indigenous groups that depend on them and occupy these areas, given that within the Western Amazon alone, there are more than a thousand documented indigenous territories and communities (data derived from the Amazon Network of Georeferenced Socioenvironmental Information, RAISG, 2009).

The social and environmental impacts of the oil and gas industry during the last four decades of large-scale production have been long-lasting in some specific areas such as North-eastern Ecuador (Buccina et al. 2013), and North-eastern Peru (Orta-Martinez & Finer, 2010). Oil and gas development is very likely to continue and increase in the near future as intergovernmental agreements and bidding rounds for new oil concessions are in course in the area (Deloitte, 2014). The main components of this projected development that would impact ecosystem services and biodiversity, are road systems and pipeline networks set up by the industries. These "oil roads" become conduits for other forms of forest exploitation and eventual land use change (Laurance, 1998). Furthermore, there have been several oil spillages and pipelines leakages that caused the release of crude oil and other toxins into the soils and waterways of the region (Kennedy & Cheong, 2009; Larrea, 2009). Similarly, extraction of gold and silver have had historic impacts of chronic release of contaminants in the region. Mining operations had always had harmful residuals, such as mercury and cyanide, which are of major concern for people and the environment (Veiga and Meech, 1995; Ashe, 2012). The Western Amazon as a region is at a crossroads where future development is imminent but this should not be at the price of losing its ecosystem services provision, and biodiversity.

1.3 Research Problem

An assessment of the past and current situation of the impacts of extractives in the Andes and Western Amazon is urgent. An evaluation of different approaches to conservation prioritisation considering the location of ecosystem services, biodiversity and potential extractive activities can provide better answers on the importance of these areas both regionally and globally and on the threats upon them that are associated with extractives. In general, it is thought that locating, understanding and then minimising the socio-environmental impacts of the extractives can help managing and maintaining the production and revenue that are indispensable for the region's economy.

Mapping the current extractive activities and infrastructure in the Western Amazon is a first step towards establishing the extent and nature of the impacts. It is then essential to define, map and compare the main ecosystem services that the area holds and whom their beneficiaries are. The use of modelling tools at this regional scale provides the necessary framework, understanding model as a computer representation of the state and behaviour of a system (e.g. conservation and development associated with oil and gas). These tools allow to establish a baseline of the current situation; and then develop scenarios as possible future conditions under given assumptions; ultimately identifying areas that should be prioritised for conservation. The need for scientific data and proper statistics for policy-making has been recognised and has proved to be of significant use in developing relevant policy (Ellison, 1996), particularly when there are conflicts on use and access to resources from different groups of society (Renn et al., 1993)

Extractives (i.e. mining and oil and gas) are by far the major component of the exports from Colombia, Ecuador and Peru (Simoes and Hidalgo, 2011), hence their sustainability over time should be analysed carefully by the local governments. Scientific information can contribute to creating a link between the industrial processes and the national environmental policies that overlook their operation. Considering the importance of ecosystem services provision, the uniqueness of their biodiversity, and at the same time the financial resources generated by the extractives, a balance between conservation and development is a challenge. It becomes imperative to bring science into action and complete thorough research to evaluate wiser options.

Even though there are several reports on localised contamination sites from extractives (Buccina et al. 2013; Orta-Martinez & Finer, 2010), and some research has been done in the oil and gas projects in the Western Amazon (Finer et al., 2008), there is a lack of research on the ecosystem services that are at risk due the extractive activities and how to prioritise their conservation. This thesis aims to fill that research gap.

1.4 AIM AND OBJECTIVES

1.4.1 AIM

The overall aim of this study is to inform a more sustainable development of extractives in the Andes and Western Amazon by highlighting the impacts they have on biodiversity, ecosystem services and how this can provide a more inclusive conservation prioritisation. The research approach to fulfil this aim uses a combination of GIS and modelling tools to propose an optimal extraction and distribution strategies with lower socio-environmental impacts.

1.4.2 OBJECTIVES

In order to achieve the intended aim, the following objectives were set to be met:

1. To determine the extent and significance of oil and gas historical activities in relation to ecosystem services in the Western Amazon, based on ground collected and remotely sensed data.

2. To develop and analyse a range of scenarios for conservation prioritisation in relation to several biodiversity and ecosystem services metrics, in order to recommend alternatives of development where extractives may take advantage of the resources with minimal damage to biodiversity and ecosystem services provision

3. To examine the significance of mining and oil and gas multiple impacts on water quality for the Andes and Western Amazon, by determining a current baseline and future development scenarios at the regional and local scales.

1.5 OVERVIEW OF THE THESIS

The thesis is composed of a total of six chapters that overall are directed to resolve the research problem around extractives impacts on biodiversity and ecosystem services, and recommend measures for conservation prioritisation, as it was summarised in the previous sections of this first chapter. Below it follows a brief description on the next chapters and how the document has been organised and presented.

1.5.1 Chapter 2 Literature Review

This chapter provides the basis to understand the issues of extractives in the region and covers key concepts of conservation prioritisation and ecosystem services, highlighting the research that has already been done, and looking to identify the gaps that this investigation covers. It first describes the geography, the history and current situation of extractives in the Andes and Western Amazon. It follows with some real examples of the impacts in the region, which were used as case studies for the modelling chapters. The importance of protected areas as the heart of conservation prioritisation is discussed, followed by the main approaches to define and classify ecosystem services globally and within the boundaries of this study.

1.5.2 Chapter 3 Multicriteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon

This chapter is presented as a published paper in a peer-reviewed journal. Hence it stands alone as a research paper, though it contributes to the overall aim. It retakes on some of the concepts and current situation of ecosystem services in the Western Amazon, and focuses on the oil industry. The research here started with a comprehensive data collection and parameter preparation effort to complete an assessment of the oil impacts, in one hand, and the potential ecosystem services, on the other, that overlay in the Western Amazon. With the development of innovative geo-visualisation techniques, it was possible to plot within the same space, both groups of variables, expressed as a bivariate choropleth map, which is both a geo-spatial and a two-axis plot.

1.5.3 Chapter 4 Evaluating different strategies for Conservation Prioritisation in the Western Amazon

This chapter is presented as a research work that evaluates a range of strategies for environmental conservation of areas of importance for ecosystem services provision, biodiversity value, and under current pressure and future threat. It describes the strengths and limitations of tools for mapping ecosystem services. Then, it applies and analyses the results of the current version of Co$ting Nature (Mulligan, 2012a; Mulligan, 2014a), a web-based GIS-enabled modelling tool of a range of ecosystem services (readily available at www.policysupport.org/costingnature). The specific functionalities of the model, coded by Mulligan (2012a), were tested, applied and analysed by the author of this thesis as part of the research process. Furthermore, this was the first time that the model was applied at a multi-tile scale and used for conservation prioritisation research. The strategies evaluated here include *i)* a prioritisation of threatened biodiversity, within oil concessions; *ii)* an emphasis on ecosystem services of global and local importance; and *iii)* an examination of areas under human pressure, thus where conservation efforts are more urgent. The results are compared and evaluated in order to identify areas that are repetitively important in all strategies.

1.5.4 Chapter 5 Analysing regional significance for Water Quality of Extractives in the Andes and Western Amazon

In this chapter, the research is aimed to examine the impacts of extractives in the eastern Andean region, part of the upper Amazon Basin, as well as the lowlands of the Western Amazon. The distribution of extractives in the areas is mapped and studied within the context of water quality. The hydrological modelling tool WaterWorld (Mulligan, 2009b; available at www.policysupport/waterworld) was used for this analysis. The model parameterisation and the development of functionalities for this research were inputs of the author of the thesis within the context of his contribution to the Challenge Programme on Water and Food (CPWF) of the Consultative Group on International Agricultural Research, CGIAR. Even more, the application and analysis carried out were pioneering for this area and for the stakeholders involved in the process. I examined and determined the baseline impacts of extractives (mining, oil and gas) under current conditions in the Andes and Western Amazon and then designed scenarios for the impacts of further development especially where these overlap important ecosystems, provider of services, as identified in the previous chapters. For instance, the measure of the human footprint on water as a surrogate for water quality, is an innovative measure to geo-visualise the potential impact extent within two basins that were used as case studies (i.e. the Coello, in the mountainous Andes; and the Tiputini, in the lowlands of the Amazon).

1.5.5 Chapter 6 Conclusions

This final chapter brings together the main findings from all the previous ones. It places the research in context, concludes with respect to the key results of each chapter, and identifies the further implications they present for the conservation research community and for policy makers involved in extractive development.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

This chapter is the basis to understand on one hand the relevance of the research problem and all its components, as well as to cover the analysis of existing research related to the extractives in the Western Amazon. It begins describing the regional perspective of the Andes and Western Amazon as one whole region bundled by their similarities on how extractive industries operate. The history of the extractives in Colombia, Ecuador, and Peru and their impact was used as the underpinning information to support the analysis in the research paper (Chapter 3). This chapter continues analysing the current situation of extractives including a few social conflicts, which are relevant as they were used as case scenarios in Chapter 5. It follows with an exploration of ecosystem services globally and regionally relevant in the area, and then discusses the current conservation priorities that are considered and the role of protected areas in this conservation strategies, which is the foundation of the work in Chapter 4. It concludes with a consideration of the ecosystem services that were considered pertinent and applicable within the boundaries of this study and that will fulfil the aim and objectives stated in the previous chapter.

2.2 THE WESTERN AMAZON AND ANDES

The area geographically defined by the Western Amazon Basin includes areas of Venezuela, Colombia, Ecuador, Peru, Bolivia and Brazil. It has been recognised as one of the largest remaining areas of intact natural ecosystems in the world (Bass et al., 2010). The Andes mountain range runs along the Western coast of the South American continent including areas of Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile and Argentina. It is the longest continental mountain range in the world spanning 7,242 km (Zimmerman, 2013) and occupying and area of more than 2,500,000 km^2 (CONDESAN, 2012). It is estimated that approximately 105 million people are directly dependent on the resources and ecosystem services the Andes provide (CONDESAN, 2012). The Andes and Western Amazon (Figure 2-1) are a source of many natural resources, particularly minerals and crude oil, which trigger the interest of extractive industries to exploit them. Ultimately, these companies aim to extract the resource in a quick and voluminous manner, thus considerations or concerns about ecosystem services are not necessarily a priority. Furthermore, extractive companies normally operate in remote areas that are uninhabited or form part of vast indigenous territories with scarce population; thus environmental policy control and enforcement are rather weak processes from a centralised system and have historically turned out to be inadequate and inefficient (Adler Miserendino, 2013; Buccina, 2013; Martinez-Alier, 2011).

2.3 OIL AND GAS EXTRACTION IN THE WESTERN AMAZON

Oil and gas fossil fuels are normally understood as one whole extractive industry (from this point forward referred as a singular oil and gas extractive). Oil and gas exploration activities in the countries of study started in the early 1900s, in the Gulf of Guayaquil, Ecuador; the area of Talara, in the northern coast of Peru; and the Magdalena River Basin in Colombia (Hanratty, 1991; Hudson, 1992). Current oil production in the three countries is variable, and not related to the size of the country but rather depends on the transport infrastructure (i.e. pipelines) and proved reserves each country has (Figure 2-2, expressed in the units, used by the industry, of barrels of oil, 1 bbl = 0.16 m^3).

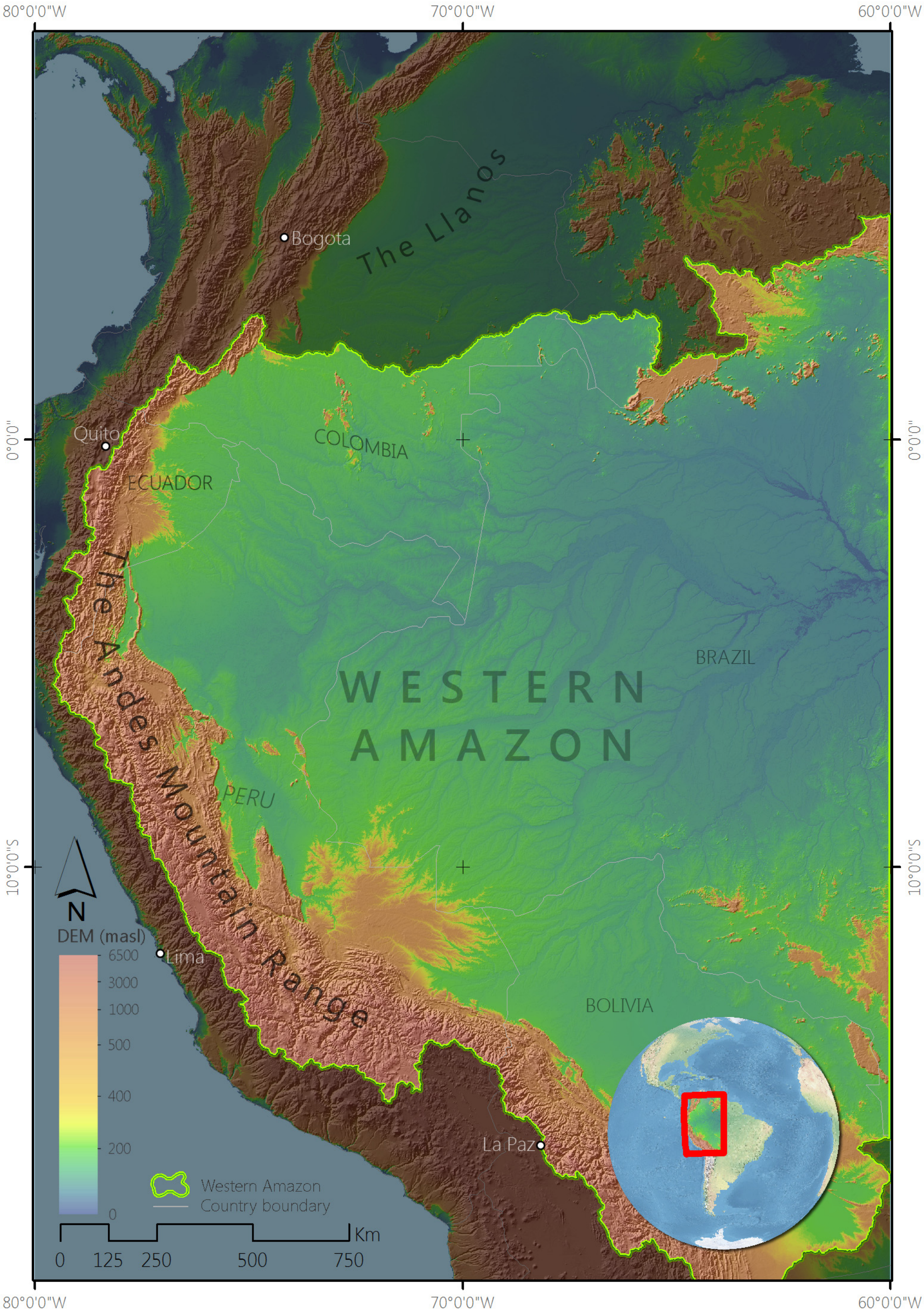

Figure 2-1 Digital elevation model, DEM, in metres above sea level (masl), of the Western Amazon showing the mountainous Andes and the lowlands in the Amazon of Colombia, Ecuador and Peru

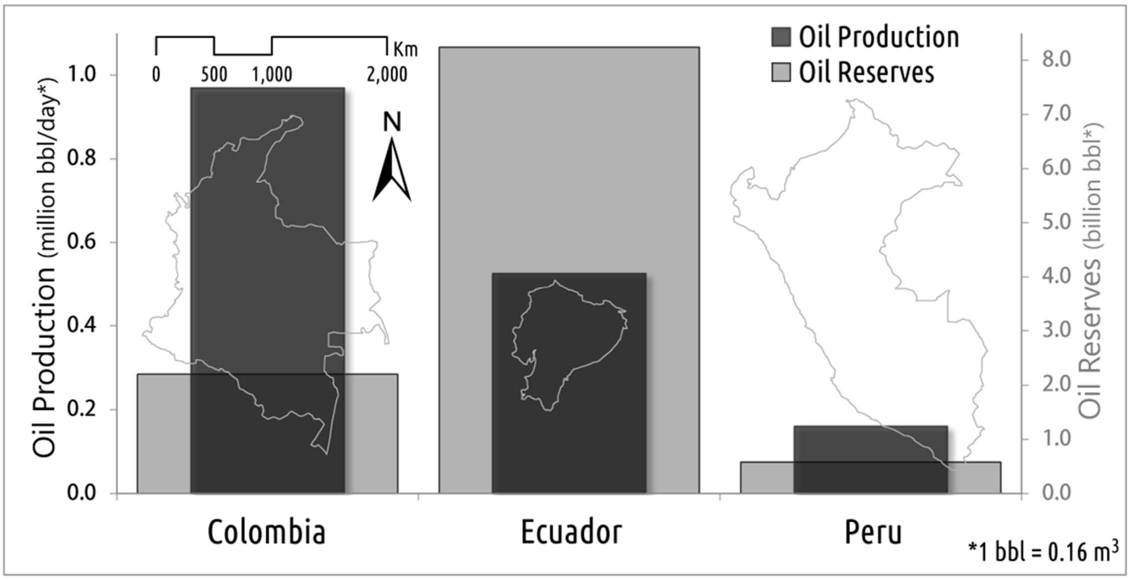

Figure 2-2 Oil production and reserves for Colombia, Ecuador and Peru according to 2013-2014 estimates (CIA, 2014), expressed in barrels of oil (1 bbl=0.16m3), and the country boundaries at scale for reference

For instance, in Colombia oil and gas operations are located on the north and north-eastern parts of the country (the Magdalena basin and the *Llanos* area, Fig. 2-1), and despite of Colombia's current oil reserves (2.2 billion bbl) being four times smaller than Ecuador's (8.2 billion bbl), its infrastructure allows for higher crude oil production (CIA, 2014; The World Bank, 2014). Proved oil reserves in Peru are comparatively the smallest at 0.58 billion barrels of oil. Conversely, figures of current oil extraction, place Colombia as the fourth top producer of crude oil in South America (0.97 million bbl/day) followed by Ecuador (0.53 million bbl/day), whilst Peru is a minor oil producer (0.16 million bbl/day) compared to its neighbours (CIA, 2014). However, future projects discussed below in Section 2.7 are very likely to change the order of this classification.

2.4 OIL INFRASTRUCTURE

The oil industry has historically been a business with enormous revenues, due to increasing demand and prices, but it equally needs considerable investment, especially when working in isolated and remote areas (Ramos and Veiga, 2011). The infrastructure and activities required for oil exploitation traditionally include: roads, wells, pipeline installations and construction of massive production facilities (Baynard, 2011). The impacts of all these infrastructures are of even greater concern when they are built in delicate and important areas for conservation, and ecosystem services.

2.4.1 PIPELINES

By 1972, the 504 km Trans Ecuadorian Pipeline, SOTE, was completed and has since carried the oil produced in the Ecuadorian Amazon fields across the Andes through an over-ground pipeline system (Mirabik, 1991; Lucero, 1997). This enabled a significant increase in oil activities in the Amazon, and due to the isolation and lack of law enforcement, many spills on land and water were produced with little or no remediation. The consequences, though not all immediate, are considered by some to be devastating (Kimerling, 1991; Sawyer, 2004). The OCP (*Oleoducto de Crudos Pesados*) is a 485-km privately-owned pipeline from the Ecuadorian fields that significantly increased the capacity for oil production since 2003, and provided extra capacity that allowed new reserves to be exploited, wells to be dug and new connecting pipelines to be set up. The OCP follows the path of the SOTE pipeline for most of its way, but contrary to the SOTE, the OCP pipes are buried several metres underground (Amazon Watch, 2003; OCP, 2010). The two main pipelines go across the Andes in Ecuador to a refinery on the coast for export. The SOTE is about 40 years old and has a history of leakage due to multiple reasons including: ageing of the pipes, traffic accidents, treefall, flooding and land slides (Lucero, 1997; Larrea, 2009). The OCP is relatively newer at 10 years old and was built for heavy crude oil with state-of-the-art technology (OCP, 2010), but it has already experienced several accidents and one big spill of 14 thousand barrels (HOY, 2009) as a result of seismic activity causing a rupture in the pipeline (Latin American Herald Tribune, 2009; Figure 2-3).

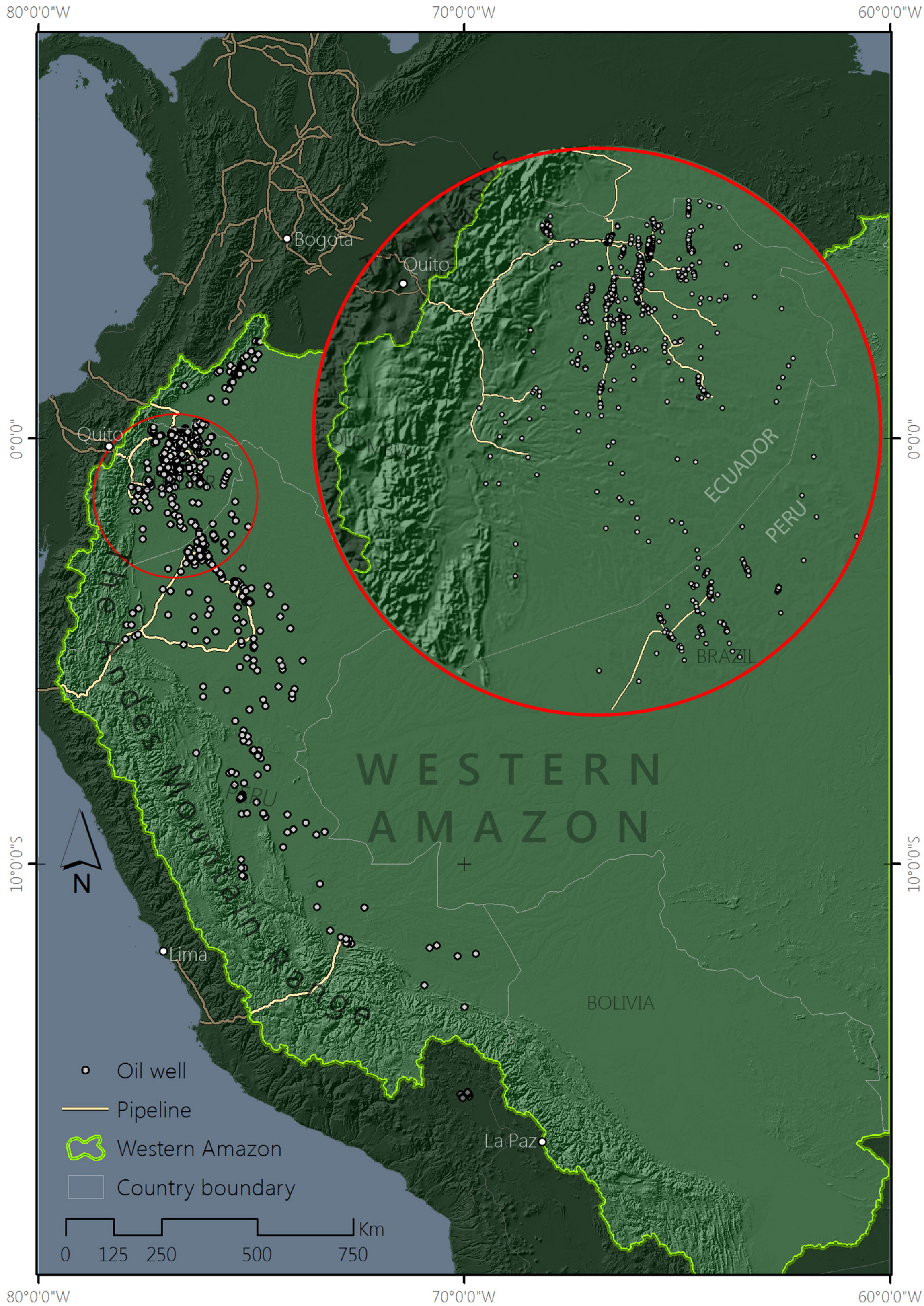

Figure 2-3 Oil and gas point and linear infrastructures in the Western Amazon, emphasising the area of highest density in Northeast Ecuador and North Peru

The national oil company in Colombia, ECOPETROL, manages the vast pipeline system (approximately 9000 Km long) divided in six main networks that cover most of the country. Close to the south border of Colombia, there is a pipeline connected with the Ecuadorian system in the Putumayo region (ECOPETROL, 2010). The current pipeline system is likely to grow towards the currently less explored areas in the Colombian Amazon, now available for investment given the improved security situation in the country and the potential peace agreements after almost five decades of internal conflicts (EIA, 2014a).

In a similar way, the oil and gas industries in Peru have constructed two major pipelines to extract their resources from the Amazon (Figure 2-3). The pipelines transport oil all the way to the Pacific Coast, for export and also provides for national demand, mainly in the highly populated capital, Lima (PERUPETRO, 2010). A report of the NGO (non-governmental organisation) Survival sent to the UN (United Nations) claims that the new 200 Km oil pipeline in the Amazonian Peru may cause severe social and environmental impacts, particularly worrying for indigenous uncontacted peoples that depend completely on the conservation of their territories (Survival, 2010; Republica, 2010).

2.4.2 Roads

In the Ecuadorian Amazon, there are three main roads of distinctive types that run parallel in a north-south direction. The first road was built in the early 1970s when the oil boom started and Texaco had an exclusive concession to operate in this part of Ecuador. The main road quickly promoted a fish-bone pattern of deforestation (Figure2-4). The government originally encouraged the deforestation of primary forest and nowadays the areas are considered inhabited and most original cover has been lost to agricultural lands, mainly cattle and subsistence crops and, a few small plantations.

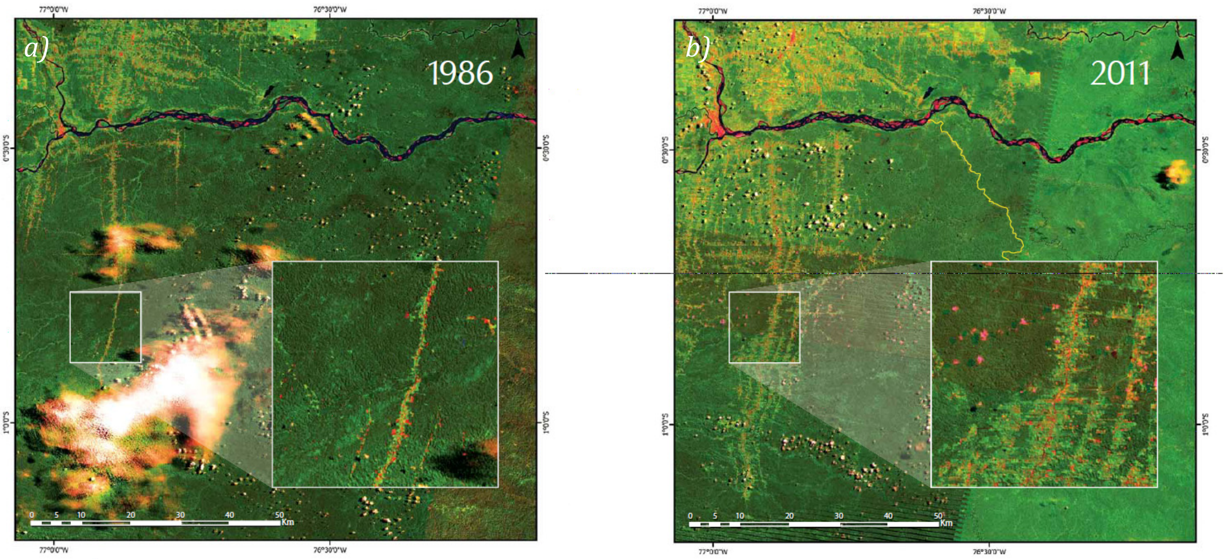

Figure 2-4 Deforestation (represented in the red pixels) around oil roads in the Ecuadorian Amazon, showing the regional and detailed fish bone pattern in *a)* 1986 and *b)* 2011, using Landsat ETM+ 7-4-2 band combination (Zurita and Borja, 2012)

The second type is a controlled-access road exclusively for oil-operatives and residents of the region (i.e. indigenous groups and colonists). An example was built in 1993 by Maxus, and is currently controlled by Repsol. It runs for 180 km north to south, and is located further east than the open road system, and cuts through Yasuni National Park and the Quechua and Waorani territories (ECOLAP and MAE, 2007). Deforestation in this area has been reduced and confined to the road zones because of the control of access. However, even for these roads an area of several kilometres of impact on the large mammals' populations has been observed. This is principally due to an extension of the hunting grounds of the indigenous and colonists, and the ease (i.e. low cost) of transporting wild meat and live wild animals to market. This is illegal wildlife trade as it is prohibited the Ecuadorian law (Suárez et al., 2009).

The third road that exists in the Ecuadorian Amazon is located furthest east and its construction was licensed by the Ministry of Environment for the exploitation of the oil concession named Block 31 assigned to the Brazilian company Petrobras. The environmental license was later revoked and the operations were put on hold. The road runs for about 14 km and it is currently abandoned and uncontrolled (Suarez et al., 2009). Petrobras did not renew its contract with the Ecuadorian government, thus PetroAmazonas, a division of Petroecuador, is in charge of developing this oil field (PetroAmazonas, 2008). Meanwhile, forest degradation and deforestation have already been observed near the road. (Oxford et al., 2012)

Similar conditions have been identified in the oil-developed areas of North-Eastern Peru, where there have been oil activities for over four decades. The road system has been equally destructive for the animal and plant populations, by “opening up” previously remote areas enabling easy access for colonisation, unsustainable hunting, and illegal logging (Finer and Orta-Martínez., 2010). These oil roads were thought to be of help for the communication of indigenous communities that ancestrally live in the area (Orta-Martínez et al., 2007); but they have rather brought severe health impacts due to increasing pollution from the extractive activities and have made indigenous groups susceptible to diseases of the outside world (Napolitano and Ryan, 2007). Furthermore, road networks have carved up the territories of ethnic groups where conflicting overlap occurs with oil and gas concessions (Orta-Martínez and Finer, 2010).

In contrast, road networks in the Colombian Amazon area of Colombia have been fairly undeveloped, thus keeping the rainforest under certain protection. This was a consequence of much of the area being under guerrilla control for the last three decades, and oil and gas demands being supplied by exploitation outside of the Amazon in the Colombian Llanos (Ristovska, 2011). However, the current government has been successful in gaining territory from guerrilla control, thus a growth of 23% in oil production was experienced during 2012 alone, partly due to expanding activities in the Amazonian concessions (Westwood, 2012; ANH, 2012). This pattern of expansion of oil activities is the same for all the countries in the Western Amazon (Finer et al., 2008; Orta-Martínez and Finer, 2010; CIA, 2010). The on-site and off-site impacts are already observed in the expanding road system.

Road networks fragment tropical rainforests creating gaps and dividing the ecosystem into sections. Habitat alteration also occurs depending on the proximity to the road, this is called the edge effect, and can have a significant influence on the biotic and abiotic processes (Kent and Coker., 1992; Zartman and Nascimento., 2006). Microclimatic changes on road edges can enable exotic plants to colonize (Enserink., 1997) and allow access for animals that migrate from outside the habitat (Buechner., 1987). Studies focusing on edge effects have found impacts on reptile distribution (Tanner and Perry., 2007), great apes (UNEP, 2002), forest birds (Gates and Gysel., 1978; Wilcove., 1985) and a rise in tree mortality due to increased windshear forces which alters the forest composition and structure (Laurence et al. 1997; Laurence et al., 2000). For example, within the Ecuadorian Amazon, oil roads stretch over 400km, and have enabled much of the Ecuadorian Amazon to suffer from high rates of deforestation and land use change from the early 1970s when they were first opened (Figure 2-5). The consequences around edge-effects specifically for oil infrastructure have not been studied, but from other research it can be assumed that they present a permanent threat on biodiversity conservation (Laurance et al., 2009).

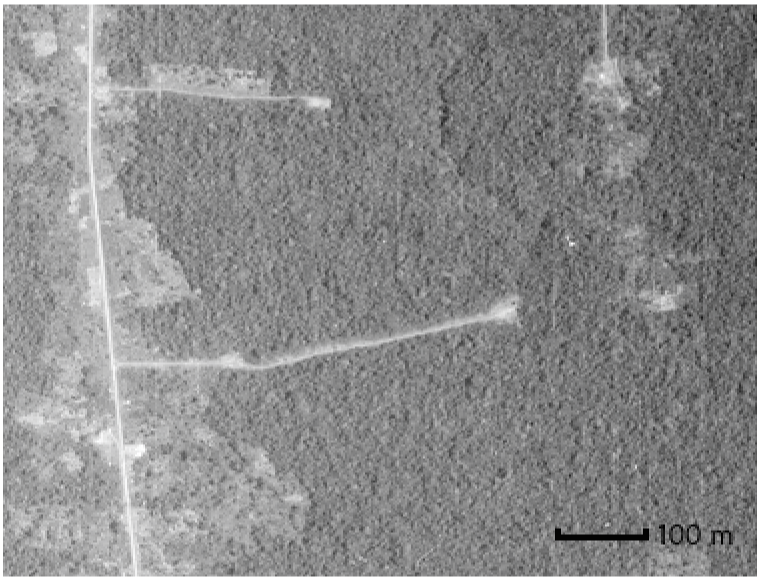

Figure 2-5 Deforestation along the road edge in the oil fields of Shushufindi, Ecuador (aerophoto, IGM, 1976)

2.4.3 Oil Wells

Oil and gas wells were drilled in high numbers during the first oil boom in the early 1970s (Lucero 1997) due to the incipient extractive facilities coping with increasing demands. The techniques used to reach the oil fields underneath were developed in the late 1800s (Kimberling, 2005). They were one-directional vertical boreholes drilled down until they reach the deposits, which eventually resulted in a high density of wells for one single field (Larrea, 2009). In fact, a preliminary analysis for this thesis showed that for the oil fields of Sacha, and Shushufindi, originally developed in the decade of 1970 the density of oil and gas wells is one for every square kilometre (Figure 2-6).

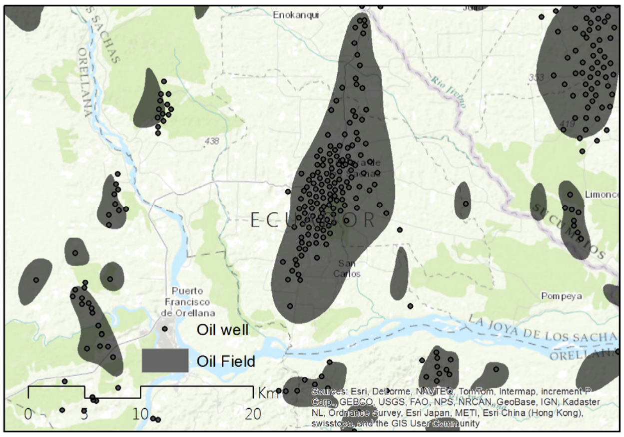

Figure 2-6 Density of *vertical* oil wells (1 well/Km²) from preliminary study in the Sacha oil field, Ecuador

Today, directional drilling techniques are the most commonly used, and allow for wells to be drilled first vertically down, between 1000-3,000 m, and then horizontally, up to a maximum of 1,500 m in several directions in the horizontal plane (Repsol 2014), thus reaching the deposits through multiple points and maximising the returns and profits, whilst minimising the impacts on the surface, and saving resources on infrastructure and transportation (Blackmon 2013). A preliminary analysis was done with directional oil wells in the Iro oil field (Figure 2-7), located within an oil and concession (Block 16) in Ecuador. This area was 'oil-developed' in the decade of 1990s with this technique, bringing down the density to one well for every 10 square kilometres (i.e. 0.1 wells/Km²).

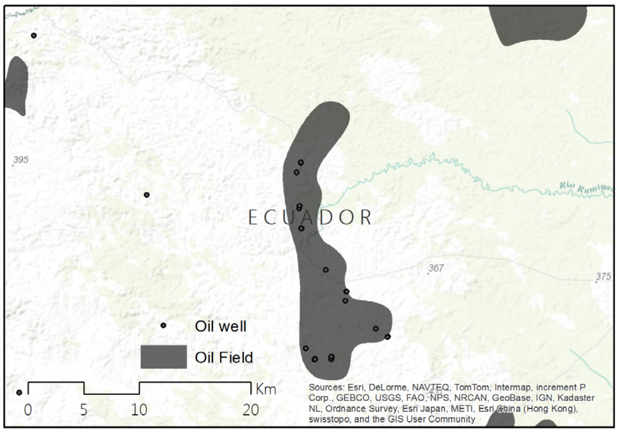

Figure 2-7 Density of *directional* oil wells (0.1 wells/Km^2) from preliminary study in the Iro field, Ecuador

Furthermore, newer techniques as the Extended Reach Drilling, ERD, allow to cover larger areas of an oil field from a single central drilling facility. These type of directional wells reach a horizontal distance double the size of their vertical depth (Finer et al., 2013), which would make and horizontal reach of around 8,000 m (Powers, 2012). ERD helps even further to minimise the impacts and requires less linear infrastructures (i.e. roads and pipelines) to be built, which is particularly important within sensitive areas. Although these techniques are slowly becoming the standard, they are still more expensive to set up by the unit than normal directional wells. Nevertheless, considering all the savings in transportation, pipeline settings and road network, they have been proved to reduce total expenses (Finer et al., 2013)

2.5 Oil in the Amazon

The oil boom for Ecuador started in the 1970s, when major oil reserves were discovered in the Eastern side of the Andes, in areas of rainforest, otherwise thought to be of no economic value. As oil production grew in this area, infrastructure also started to propagate without major control and with inappropriate planning in terms of population and land distribution (Gondard and Mazurek, 2001). These meant that environmental policy enforcement was very minimal, and new access roads were built for the only purpose of oil extraction in previously inaccessible areas. Subsequently, colonisation of these “new” territories was facilitated by the oil roads.

As a result, small oil-towns and a network of dirt roads connecting the oil fields were built, causing several indirect and off-site impacts, such as deforestation, loss of habitat of natural species, human colonisation, and exploitation of other natural resources (Suárez et al., 2009; Laurance et al., 2009; Laurance et al., 2002). These developments, originated with the oil incursion into the Ecuadorian Amazon, were particularly damaging because of the lack of consideration of additional factors such as potential impacts on ecosystem services, conservation of biodiversity, presence of protected areas, and observance to indigenous territories.

2.5.1 Oil and Gas Concessions

The first large and profitable oil reserves were found in the north-eastern part of Ecuador, and consequently most oil activities were focused in this area. However, all the Ecuadorian Amazon and soon a more extensive area of the Peruvian Amazon were rapidly explored and divided in oil blocks that roughly follow the distribution of underground oil reserves (de la Maza Elvira et al., 2003; Finer et al., 2008). However, little concern was given in this process to the location of protected areas that were created almost in parallel, and indigenous territories that have been there for centuries (de la Maza Elvira et al., 2003; ECOLAP and MAE, 2007). Oil and gas concessions cover 65% of the Amazon in Ecuador, and 72% in Peru (Finer etl al., 2008), leaving little room for strict conservation and traditional use by indigenous groups. In fact, when the oil concessions were designed, there was little coordination with the environmental institutions, and more crucially there was no concern about –nor prior consent from– the inhabitants of the area (Finer et al., 2008). The result of this process is a series of overlapping concessions, protected areas and indigenous territories; which in turn have created a mosaic of environmental and social conflicts, such as those found in Peru (Figure 2-8). Previous works have highlighted these overlaps and their implications on biodiversity (Butt et al., 2013; Finer et al., 2008), but there is still work to be done in the inclusion of ecosystem services in this type of analyses.

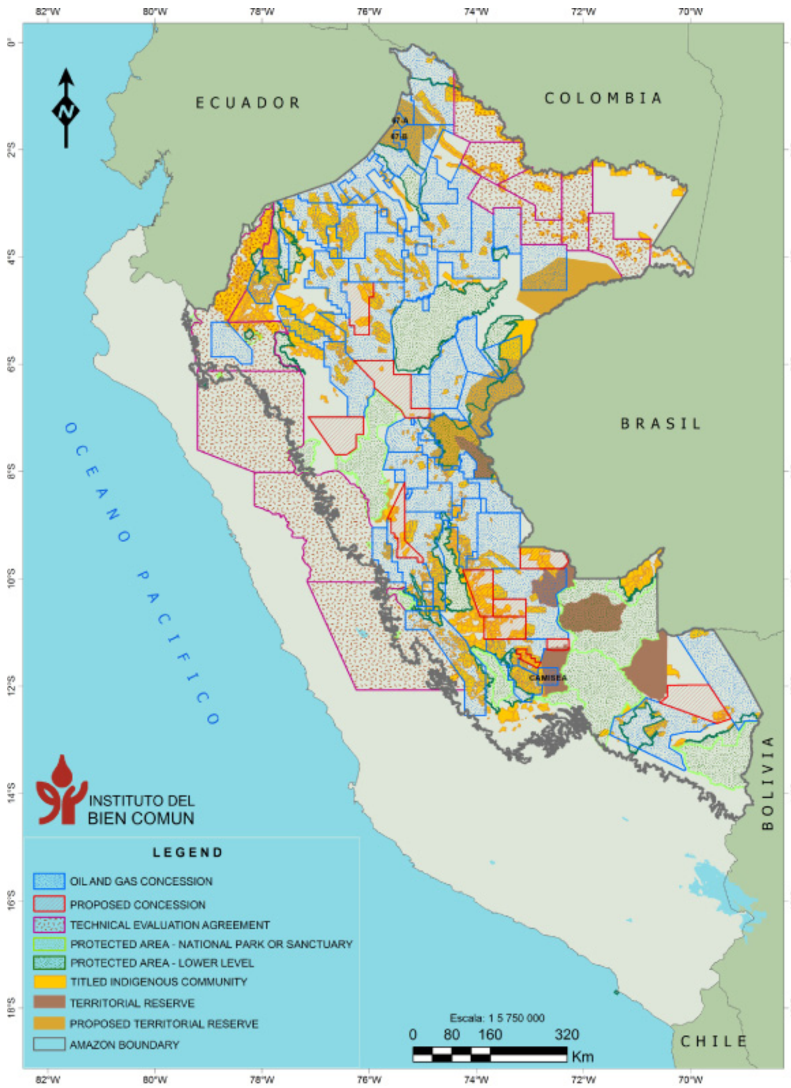

Figure 2-8 Oil and gas concessions in the Peruvian Amazon overlaying protected areas and indigenous territories (IBC *in* Finer and Orta-Martinez, 2010)

2.5.2 Hydrocarbon Extraction Policy and Oil Companies in Ecuador

The driving force for national governments when the oil production started, and also to a certain extent today, is to maximise the profits, and minimise the costs of extraction, whilst paying less attention to the social and environmental impacts of these extractive activities. In

Ecuador, the Mines Code was the law guiding the extraction of natural resources from 1903 until 1972, when the Hydrocarbons Law (Ley de Hidrocarburos) was passed in Congress and created the national oil company CEPE (*Corporación Estatal Petrolera Ecuatoriana*) that operated as a consortium with the private company Texaco Gulf (now Chevron Texaco) from the United States (Lucero, 1997). CEPE became a large bureaucratic body and due to corruption (Kimerling, 1991) and inappropriate planning and investment strategies went practically bankrupt and it was replaced by the new national company Petroecuador in 1989 (Larrea, 2009). At the moment, the national oil company manages half of the oil production in the country, and foreign investment accounts for the other half. The main companies that are currently leased to extract oil in Ecuador are Repsol-YPF (Spain), Andes Petroleum (China), Eni (Italy), Petrobras (Brazil), ENAP (Chile), and more recently through a bilateral government agreement, PDVSA (Venezuela)(CIA, 2010; PETROECUADOR, 2010).

A report from the local NGO working for the defence of local communities' rights to a healthy environment reported a total of 18 billion gallons (68 Mm^3) of liquid pollutants were dumped into the waters of the Ecuadorian Amazon to date, most of them known to be carcinogens (Amazon Watch, 2009). Additionally, an estimated 900 open-air pits were dug, with no protection from infiltration to groundwater sources (FDA, 2013). Moreover, several million tons of CO_2 are estimated to have been released through permanently burning gas flares on wells - a practice which continues even today (Larrea, 2009). Texaco (now part of Chevron) was the sole international operator for oil fields discovered in eastern Ecuador from 1969 to 1992 (Texaco, 2010). These reserves secured a profit that was expected to help bring the country out of poverty. However, as seen in other countries, the revenues did not accomplish the expectations and, what is worse, the oil industry became a major source of contamination (Watts, 2001). The environmental policies for the oil activities were too general or non-existent and thus did not provide robust protection to the environment and populations of the Amazon. Furthermore, international companies were not legally obliged to and sometimes chose not to apply the same level of environmental regulation that they are required to apply in their home countries.

Texaco ended its contract and activities in Ecuador by 1992. From that point forward, the national oil company –Petroecuador– took over the operation of the oil fields, retaining the same outdated technology and practices. In November 1993, a class action lawsuit was filed in a New York court against Texaco on behalf of 30,000 people of the Ecuadorian Amazon, whose environment and livelihoods were affected by contamination (Amazon Watch, 2009; Watts, 2001). The lawsuit went through different stages of dismissal and appeal. In 1998, Texaco signed a settlement agreement with the Ecuadorian authorities, for their partial and poorly carried out remediation of a small percentage of the open-pits they created and filled with crude oil and other toxic substances. In 2001, Texaco was acquired by Chevron, which inherited its liability on this lawsuit among others. By 2003, the case was transferred to a local court in Nueva Loja, Ecuador, with jurisdiction over the area where the environmental damage took place. A total of 122 judicial inspections of the oil pits were ordered, representing a sample of 10% of the oil pit sites. Finally, after 18 years of litigation, Chevron was fined a total of USD18bn, which is the second largest corporate fine ever applied, only surpassed by the most recent British Petroleum compensation fund for the Gulf of Mexico oil spill, of USD20bn (Martínez Alier, 2011; Carus, 2011; Amazon Watch, 2009; Chevron, 2007). The company is not conceding responsibility and is looking at ways to appeal and not pay the fine. Meanwhile, the oil contamination and its effects remain.

2.3.3 Oil institutions

The 2010 Hydrocarbons Law of Ecuador, passed by the recently formed National Assembly, changes the oil situation by giving the Ecuadorian Government a greater share of the profits and more control over contracts with foreign companies, since these companies are now considered as service providers for the State. At the same time, the government has more responsibility for the operation and impacts of the oil industry. This raises important questions about the institutional strength of the renewed Ministry of Non-Renewable Natural Resources, and the influence that the Ministry of Environment will have over the policies that the former will be making and enforcing.

Over recent years there has been a trend towards nationalising hydrocarbon resources in Ecuador, with 73% of total production today being accounted for by national oil companies (EIA, 2014b). National oil companies include Petroamazonas, Petroecuador, and Operaciones Rio Napo, which is a joint project with Petroecuador and Petroleos de Venezuela. The rest of production is accounted for by international oil companies including Eni (Italy), Repsol (Spain) and Chinese companies such as Enap and Andes Petroleum (EIA, 2014b). Ecuadorian hydrocarbon resources are owned by the state and offer a fixed barrel fee to foreign investors, this is a move away from the production sharing agreements, which were less profitable for the government (EIA, 2014).

2.6 The Yasuni-ITT initiative to stop oil development

The trend in all three countries of the Western Amazon, and for that matter in most oil-producing countries in the world, is to increase production and expand oil infrastructure. The partitioning of new blocks shows this tendency and negotiations for future developments with foreign companies already starting in the new oil blocks in north-eastern Peru, and a similar situation is foreseen in Ecuador now that the new Hydrocarbons Law is in place. Until 2013, the only major project that went against this trend was the Yasuni-ITT initiative, endorsed by the government of Ecuador and aimed to maintain permanently untapped the biggest proven crude oil reserve (8.5×10^8 bbl) of the country, in exchange for international funds that cover half the opportunity-cost of extracting that oil (Figure 2-9). The appeal was directed to the International Community as part of inter-governmental agreements associated with the UNFCCC (United Nations Framework Convention on Climate Change). Even more, the

Ecuadorian and international civil society was targeted as a minor –in terms of funds– but important –in terms of numbers and incidence– donor and contributor to the cause (Larrea and Warnars, 2009; Rival, in press).

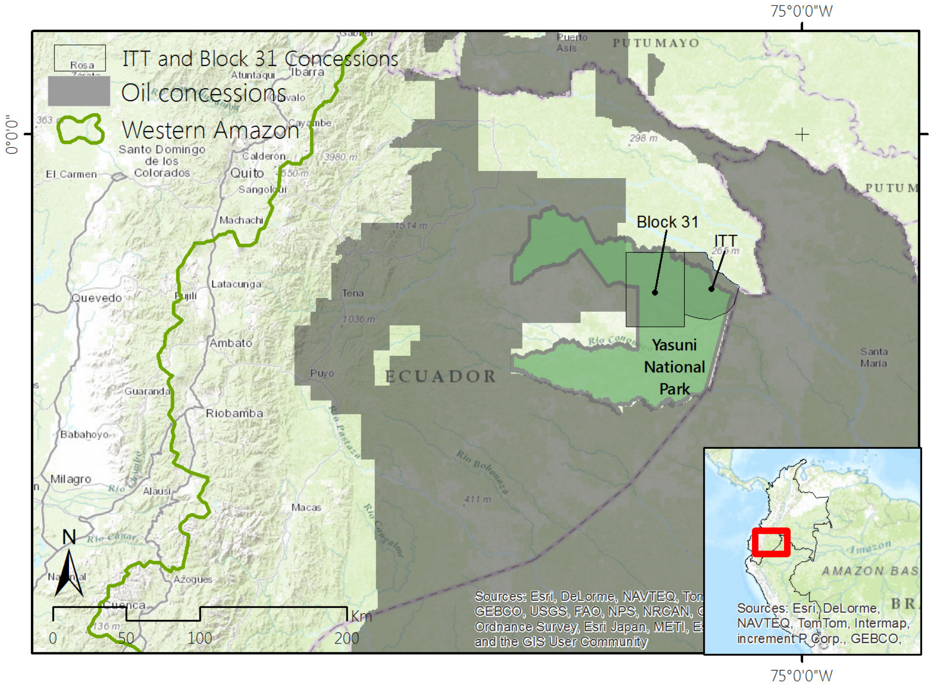

Figure 2-9 Yasuni National Park and the overlaying oil and gas concessions, distinguishing Block 31 and ITT concessions

The Yasuni-ITT initiative was dismantled on the 15th August 2013 by Ecuador's President Rafael Correa (EIA, 2014b). The government stated that this was due to unsuccessful efforts to raise international contributions, of half the market value of the 850 million barrels of oil in the ITT, therefore it was in the nation's interest to commence the development of hydrocarbon resources in the ITT fields (Lang, 2013). Correa stated that the oil exploration would only affect less than 1% of the national park. However, these figures are taken from an impact study by PetroAmazonas (a division of the state oil company PetroEcuador) of a plan to drill 32 wells in the Tambococha and Tiputini oil fields and ignores the planned 3D seismic tests which expand over 100,000 hectares of the national park, which suggests that the operations would expand much further (Hill, 2013).

The Yasuni National Park (Figure 2-9) is one of the most biologically diverse habitats in the world, being a UNESCO Biosphere reserve since 1989 (UNESCO, 2009). Bass et al. (2010) argue that Yasuni is significantly important for global conservation due to its large size and intact large vertebrate assemblages, along with the predictions that it will have a high chance of maintaining the wet rainforest conditions with the anticipated climate change. Environmental groups and conservationists are fighting to keep oil exploration out of the national park by forcing a referendum on Correa's plans. At the beginning of April 2014, environmentalists in Ecuador state that they have collected enough signatures to hold a referendum with 727,947 people signing a petition, which is enough required by Ecuadorian law (BBC, 2014).

2.7 FUTURE DEVELOPMENT OF OIL CONCESSIONS

The Yasuni-ITT initiative was a positive example of recognising the value of key ecosystems and their services, even where conflicts with economically important natural resources exist. This 'conservation' scenario should be weighed against the 'Plan B' (i.e. oil development) using a spatio-temporal modelling tool in order to properly estimate the potential benefits and impacts could be and determine the trade-offs of each scenario. Hence, a baseline scenario of the current situation is needed to start this analysis, beginning with the current linear infrastructures (i.e. roads, pipelines) in the Western Amazon (Finer et al., 2008; Laurance et al., 2009). They have caused, and still are causing, an impact on the environment and thus ecosystem services provision, in the form of changes in forest cover (Sierra, 2000); affecting faunal population dynamics (Goosem, 2004), impairing human health (San Sebastián and Hurtig, 2005; Hurtig and San Sebastián, 2002), causing acculturation of indigenous peoples in the area (Rival 2002), to name a few, that are well documented (Finer et al., 2008; Suárez et al., 2009; Orta-Martínez et al., 2007).

With that baseline scenario established, the proposed development can be modelled according to different scenarios. For instance, the pipelines that will be deployed across the newly leased concessions will add on to the previous impacts. This change (i.e. delta) is the key to measure the actual impact of oil and gas future developments. Furthermore, recommended best practices, such as those studied by Finer et al. (2013) and Powers (2012) can be further analysed and actually modelled to be compared with current drilling techniques.

Even though, Environmental Impact Assessments, EIA, and mitigation measures are regulated by law, they are always focused at local and site-specific scale and do not take account of the collective impact of multiple point or linear developments (Goosem, 2004). Since oil infrastructures usually cover long distances of pipelines and a network of wells, it is important to assess them in a regional context, so that all the collective impacts of development are taken into account, particularly with respect to their effect on ecosystem services. Moreover considering that these on-site impacts of an extractive activity can potentially be transmitted to off-site areas. For example, the release of a contaminant close to a water stream, can and will travel downstream to off-site areas that could potentially be located hundreds of kilometres downstream (Tarras-Wahlberg et al., 2001).

As described before, Ecuador already has two major oil pipelines, and additionally it has a connection with a Colombian pipeline to transport oil to the Pacific Coast. A similar situation can be observed in Peru, with two main oil and gas pipelines that start in the Eastern lowlands, pass over the Andes and make their way down to the coast again, trespassing important natural areas and some indigenous territories (PERUPETRO, 2010; Orta-Martínez and Finer, 2010) Moreover, projects are underway for a three decade contract to construct and operate two additional major pipelines in Southern Peru, that will fragment important areas of conservation (Republica, 2010; Gurmendi, 2004). Currently, Ecuador's ITT oil reserves are set to be developed, now that the Yasuni-ITT initiative was dismissed, together with the adjacent blocks to make the project feasible and more profitable (Araujo, 2014). Even more, the currently open bid round XI for new 33 oil concessions in southeastern Ecuador will connect in the near future the North-Peruvian oil pipeline with the Ecuadorian projected pipelines

(Deloitte, 2014; Presidency of Ecuador, 2012) Therefore, working at the regional and international scale will allow to properly see the whole picture and realistically estimate the future development scenarios of oil and gas concessions. This was precisely studied in the last empirical section (Chapter 5) of this thesis.

2.8 Mining of Precious Metals

2.8.1 History of Mining

The Andes and Western Amazon are the source of natural resources for a range of extractives and have been undergoing major changes for the past four decades. Oil and gas extraction has extended over a large area of the Amazon, whilst mining of minerals and precious metals is mainly concentrated in the mountainous areas of the Andes, and to a lesser extent in the Amazon lowlands. The extractive activities depend upon techniques that have always produced hazardous residues. Production water is a key by-product of oil and gas extraction, and even though it occurs naturally in the deep subsurface, it is a cause of major concern when it is brought to the surface due to the volume and high concentration of known carcinogens present within it (Veil et al., 2004, Amazon Watch, 2009). Poor practices invoked to reduce production costs led to the release of an estimated 18 billion gallons (68 Mm^3) of pollutants in the river network of the Ecuadorian Northeast Amazon over a period of three decades of oil exploitation from the early 1970s (Keefe, 2012), during which *only* 1.5 billion barrels (238 Mm^3) of crude oil were produced and transported (Kimberling, 2005).

The residuals from mining for precious metals are more varied. The main concern is the use and pollution of surface water resources during the mining process. Malm (1998) calculated that, due to the gold mining in Brazil during a period of 20 years, there were at least 2,000 metric tonnes (2 Gg) of mercury released into the environment, especially to water. Some pollutants are released into the atmosphere and are of great concern at the local level. Other residuals are dissolved in the water used in the mining process, and these are of greater concern at the local and regional scales due to their transportation downstream. Moreover, the bio-accumulation of these contaminants in food sources causes the magnification of hazardous effects up to threatening levels when going up in the food chain. In the surroundings of mining sites in Brazil (Negro River and Madeira River), and Peru (Madre de Dios and Puerto Maldonado) the bio-accumulation of mercury within entire communities living on the riverbanks and, hence dependent on fishing as a food source have been found to be above maximum levels as established by the World Health Organisation (Swenson et al., 2011, Barbosa et al., 2001, Malm, 1998). These dangerous levels pose a significant threat to the environment and health of nearby inhabitants. Even though trace elements such as mercury, occur naturally in the environment, high levels and prolonged exposure have been proven to be harmful, causing itching, burning and localised pain, as well as inhibiting the normal functioning of certain enzymes, which can lead to tachycardia and hypertension (Olaf, 1998). The organic variant of mercury (measured as methyl-mercury) is particularly toxic, and it has been observed to reach levels between 70-90% of the total mercury released as residues of mining through amalgamation (Ashe, 2012, Akagi et al., 1995). The origin of this residues show that on-site contamination, is then transported via the flow network downstream. That means, in addition to the people directly working in the mining operations, the environment, flora, fauna and the general population living and depending on the rivers as food sources (Barbosa et al., 2001) are also exposed.

2.8.2 Techniques of mining extraction

Several amalgamation methods that combine minerals and salts containing mercury and other metals were used historically from the Spanish colonial times in Latin America to retrieve both silver and gold (Nriagu, 1994), until after centuries of heavy use of mercury and release of harmful residuals to the environment, more efficient techniques started to replace it. However, due to the high constantly rising gold prices – a 360% increase in the last decade alone with current prices of 1300 USD/oz., as established by the World Gold Council, (WGC, 2014b)– there has been an artisanal and often illegal gold rush over the last three decades(Ashe, 2012). This has brought back the amalgamation techniques and even though the elemental mercury is recovered and reused, there is a ratio of loss of 1.32 parts of mercury for every 1 part of gold produced (de Lacerda and Salomons, 1998). Considering that Latin America currently supplies around 20% of the global gold production, and between 20-30% comes from artisanal origins (Ashe, 2012), with a total annual production from mines of 3,000 Mg of gold (WGC, 2014a), the hazardous residuals of mercury can amount to no less than 120 Mg per year in the rivers of South America. One third of the total mercury released globally into the environment is believed to come from these types of mining techniques (Telmer and Veiga, 2009).

Due to the high investments, and profits, of the mining industry, research has been directed towards finding more efficient techniques that allow to obtain more metal from the mineral ores. These techniques may improve the efficiency of the processes and also reduce impacts on the environment, but they are not free from hazardous residuals (Hilson and Monhemius, 2006). For industrial mining, technical processes using cyanide leaching have been in use for almost a century. This technique is considered to be more efficient in terms of metallic production, though it takes higher investments, a larger infrastructure and longer processing time than amalgamation (Barbosa et al., 2001). However, cyanide is capable of killing a person if ingested in high doses (Logsdon et al., 1999). From mining, the impacts of cyanide dissolved in water are known to be lethal for the aquatic fauna where high concentrations have been reached by bad practices and accidents in handling the residues that the mine tailing dams hold back (Rico et al., 2008).

2.9 Impacts of Extractives on the Environment and Social conflicts

The social conflicts and environmental concerns in both these extractive industries are relevant, independent of where they operate. Every case will have its peculiarities, but there are certain generalities that can be identified: a) the interest of the companies is to maximise their profits by minimising the costs of operation b) the extractives need to comply with local, and international regulations. Particularly in Latin America, extractives have recently boomed due to increased access to remote locations and new bilateral and multilateral cooperation agreements (Deloitte 2014). In fact, truncated accessibility to some of these areas has been of positive effect towards their conservation. At the same time, being physically far from the central government offices where decisions are made, has left them isolated from carefully controlled development. Many of these rural areas lack basic services and people's means of subsistence depend, even if it is unknowingly, on the maintenance of local ecosystem services (e.g. water provision, climate regulation, hazard mitigation, amongst others). This lack of development and state presence, has created a niche for the extractives to contribute towards local development. Several services, such as electricity, road maintenance, sewage and rubbish disposal, and even basic health and education are provided by the companies as part of their community relationship programmes, contributing to corporate social responsibility goals (Repsol, 2012; PETROECUADOR, 2014; AngloGold-Ashanti, 2004; Vale, 2012). However, the long-term social conflicts and environmental impacts of these industries are commonly overlooked and could potentially surpass any benefits this development may bring in the short term (Martínez Alier, 2000).

Global and regional GIS studies have addressed and shed light over the current and future impacts of extractives on biodiversity taking into account areas under protection as well as species richness and threatened species (Butt et al., 2013; Osti et al., 2011). The threats of direct and indirect impacts on biodiversity within oil and gas concessions are of particular concern in countries with weak governance and centralised government agencies that allow for a loose environmental control (Butt et al., 2013). These analyses have drawn attention to the issue of extractives impacts on biodiversity, which in turn has brought positive attention of both the industry and the conservation sectors, though the overlay and proximity analysis can result too simplistic (Deichmann and Alonso, 2013). Considerations of water networks that transport these impacts downstream, inclusion of more relevant variables for conservation such as ecosystem services, and a more approachable platform for all stakeholders, are thought to be an improvement on these analyses and would yield more realistic results.

2.9.1 THE CASE OF THE TIPUTINI RIVER AND THE WAORANI

The case of the Waorani people, in Ecuador, shows how this semi-nomadic group of hunters and gatherers whom have occupied, for over 5,000 years a territory of 25,000 Km^2 between the Tiputini and Curaray rivers, were forced to change their life-style and culture following the first contact made by missionaries of the Summer Institute of Linguistics in 1958 (Rival, 2002, Haro-Pastor and Donati, 2008). Since then, their means of subsistence have been significantly impaired due to the oil development and they have been acculturated into new economies depending on cash instead of forest resources and new needs that were unknown, and unnecessary, before have now been introduced (Orellana, 2004). Two sub-groups of the Waorani, named the Tagaeri and Taromenane, are thought to be living in voluntary-isolation, avoiding contact with the external world and occupying the most remote areas of their territory in the rainforest. An “untouchable” reserve of 7,000 Km^2 was designated by the Ecuadorian government, in 2007, named the *Zona Intangible* (Finer et al., 2008) to accommodate these peoples in isolation. However, this reserve is already overlapped by oil concessions, and its boundaries, as officially redacted in the Presidential Decree, are geographically inconsistent and are under permanent threat due to the untapped oil reserves (Pappalardo et al., 2013). Conflicts, actual attacks and deplorable episodes of genocide have occurred against the Tagaeri and Taromenane groups, violating their traditional territory, and voiding their will to live without contact with the Western World (Chavez Vallejo 2003). The actual implications of this anthropological case in point are beyond the scope of this thesis, but it is important to highlight them as part of the discussion around extractives. Furthermore, these isolated groups should be considered despite, or precisely because, of their inability to take part in the debate. The consideration of the cultural services that the Tiputini basin provides for the Waorani and the humanity in general have been considered (UNESCO, 2009) but it is rather difficult to assign a value or quantify them.

2.9.2 The case of the Grand Coello

The people of the Grand Coello Basin, which includes both the Combeima and Coello Rivers, depend on the river water for agricultural, cattle and general consumption and the impact of these activities has already been identified in the Management and Ordinance Plan for the Grand Coello Basin, POMCA (*Plan de Ordenacion y Manejo de la Cuenca Hidrografica Mayor del Rio Coello*). The plan recognises the vulnerability of the aquifers to extractive activities and the consequent water stress this may cause, particularly to urban consumers of the city of Ibague, the eighth largest city (by population) in Colombia (Cortolima, 2005). In 2008, the Colombian Geological Service, INGEOMINAS, granted exploration permits for gold mining over a 500Ha area to the South African company AngloGold Ashanti, (AGA). The concessions awarded overlap with National Forest Reserve areas, where all extractive activities are prohibited (Perez Rincon, 2014). The concession also includes areas above 3200 m. where *paramo* ecosystems are found and, as sources of clean water, are subject of special protection under Colombian Law, considering them a natural heritage (Colombia Solidarity Campaign, 2013). The threat of mining development was replied to with a massive social movement and through communal organisation the exploratory activities were halted, in 2011, until further notice due to the environmental and social concerns (Perez Rincon, 2014). On the other hand, the technical reports of the company and their public communications focused on how the land tenure is being handled and their financial contributions to the local communities (AngloGold-Ashanti, 2014). They fail to mention how they plan to address the considerable amount of waste rock and tailings (Higman, 2014) that a mining activity of the scale proposed would produce. In fact, using estimates of potential gold production released by AGA, the Colombia

Solidarity Campaign (2013) calculated that 100 million tonnes of waste rock, and 1,420 million tonnes of tailings will be a by-product of the extraction, with a water use, at the lowest estimates, equivalent to the normal consumption of 1.25 million people. These numbers result in several valleys potentially covered with waste rock, the biggest tailings dam in the world built to hold the highly toxic residuals of the mining leaching activities, and a water demand greater than that for the whole administrative region of influence would need to be dedicated exclusively to cover this extractive activity. Completion and submission of the environmental impact assessment, EIA, will be by early 2015, but the exploratory activities have restarted and, exploitation and production is expected to start by 2019 (AngloGold-Ashanti, 2012).

These two case studies were used in the data chapters due to their relevance and field data availability. Additional case studies that were also researched and relevant in the area are detailed in Appendix A.

In all of the cited cases, the lack of information, or misinformation, has been a common denominator. Regulatory agencies, within Secretaries of the Ministry of Environment in Colombia, Ecuador and Peru, have to deal with both large scale and artisanal mining permits. However, in many cases they are not able to cope with the number of requests and even less with the enforcement and regulation of the actual operations. Thus, illegal mining activities, mainly at small and medium scale, have grown and spread in remote areas (Sinding, 2005; Ashe, 2012) throughout the Andes. The immediate consequences are deforestation and contamination of waterways at the local level. Moreover, these threats can easily spread regionally, in the near future, if proper planning and policy enforcement are not implemented since new infrastructure can be much more economically added to existing operations where these have 'opened up' previously remote areas.

Mining, and Oil and gas extraction account for considerable portions of the Gross Domestic Product, GDP, in the focus countries of this study. In fact, Ecuador and Colombia's major export by value in 2011 was crude oil at 50% and 45% respectively, whilst Peru's major exports for the same year were Gold, 21%, and Copper, 16% (Simoes and Hidalgo, 2011). Furthermore, these products have made up more than a quarter of the GDP, for all these countries for all years in the last two decades (Hausmann et al., 2011, Banco Central del Ecuador, 2014, Banco de la Republica, 2014, Banco Central de Reserva del Peru, 2014). Consequently, the future promises to bring further infrastructural development to expand these industries within the region (Finer and Martí, 2010), as illustrated by the Initiative for the Integration of Regional Infrastructure in South America, IIRSA, that aims to develop more than 30 regional infrastructural projects (IIRSA, 2013) in the next decade.

2.10 Protected areas

Protected areas are used to conserve nature and classify regions that are of international importance in regards to the species and ecosystems, they are the foundation of global conservation efforts. The nomenclature differs amongst them, but a common global approach are the IUCN (International Union for Conservation of Nature) categories, which include: Strict Nature Reserve (Category Ia), Wilderness area (Ib), National Park (II), National Monument or feature (III), Habitat/Species Management area (IV), Protected landscape/Seascape (V) and Protected Area with sustainable use of natural resources (VI).

The three countries of the Western Amazon have in total 175 terrestrial protected areas under some IUCN category, which cover in average 16% of their land (UNEP-WCMC, 2012), These areas include a considerable number of species listed under some CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) Appendices including 900 bird species, 300 mammals and around 250 species of invertebrates, and a current biodiversity loss of 10% from its assumed natural original state (UNEP-WCMC, 2014). The pressure of human activities on biodiversity is thought to be minimised within and around the protected areas, hence their importance and considerations as priorities for conservation (Jenkins, et al. 2013)

Due to the high biodiversity of the Western Amazon, the current pressure it is under, and the weak governance over these remote and mainly undisturbed areas, it is considered under great risk (Butt et al., 2013). Nevertheless, there are conservation efforts aimed to strengthen protected areas across these boundaries (RAISG, 2012b). Traditionally protected areas were created to maintain, support and promote biodiversity and natural heritage. The establishment of protected areas were built of two major movements. Until the 1960s motivation relied on 'national romanticism' and the preservation of aesthetic landscapes (Tuvi et al., 2011). Succeeding this, during the first Worlds Parks Congress in 1962, protected area establishment was defined for the protection of biological diversity, and approximately 80% of protected areas were created post 1960s (Chape et al., 2003).

Currently, the IUCN, through its World Commission on Protected Areas, WCPA, defines protected areas as "*a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values*" (Dudley, 2008, p.8). It is now understood that protected areas not only provide a solution for biodiversity conservation, but they also are a source of vital ecosystem services that produce great economic benefits and are integral to community well-being (Lopoukinhe et al., 2012). This approach to factoring in ecosystem services when considering the establishment of protected areas is relatively recent but increasingly important. In the Western Amazon, protected areas are known for being home of unique, abundant and threatened biodiversity, which is the main argument for their conservation (Bass et al., 2006; Jenkins et al., 2013) but they also provide crucial global and local ecosystem services. These include; carbon services, climate regulation and hazard mitigation (reducing the risk of natural disasters), water security and its associated agricultural production (Balmford et al., 2002). Evidence also shows that large networks and connected protected areas provide adaptation and refuge in threat posed by climate change and its response measures (Crooks and Sanjayan, 2006; Rogers and McCarty, 2000). In recognition of this the International Union for Conservation for Nature (IUCN) has placed the expansion, connectivity and sensible management of protected areas on the forefront of the agenda as one of the three priority objectives for the World Parks Congress, 2014 (IUCN, 2014). The expansion of protected areas is being increasingly considered as a proactive and cost-effective approach to curb tropical deforestation and carbon emissions (Laurance et al., 2009). Another solution may also be to apply conservation management transnationally, transcending protected areas boundaries and extending to buffer zones, mosaics of protected areas, biological corridors and stepping stones (Lopoukinhe et al., 2012), responding in that way to the globalisation of extraction of resources.

For instance, the Yasuni National Park and the Yasuni Biosphere Reserve form together one of the largest protected areas with mostly pristine forest in the Western Amazon covering a landmass of 1.6 million hectares (Valencia et al., 2004). One of the main threats to this protected area are roads and other linear cleanings (Laurance et al., 2009). This is particularly true when considering the impact of frontier roads in increasing access to and opening up remote virgin rainforest (Fearnside, 2007). Laurance et al. (2009) argue that the highest priorities of conservation managers should be maintaining large, roadless areas of forest as many ecological specialist species avoid strips of forest less than 30m wide. When road building cannot be avoided, implementing protected areas along the road route can reduce deforestation and further invasions. This was found to be successful in Brazil, where there was less forest loss along the Cuiaba-Santarem highway in places where there were protected areas in place prior to the road construction compared to regions with few protected areas (Laurance et al., 2002).

Creating corridors between the protected areas can prevent wildlife populations from becoming isolated thereby reducing genetic and demographic threats (Wikramanayake et al., 2004). Bass et al. (2010) recommendations are a good example of conservation prioritisation around existing protected areas. They concluded that *a)*Yasuni should have protected biological corridors to connect the lowland Amazon the nearby Andean Parks, in order to enable species to move up with climate change; *b)* a corridor should be established from Yasuni to the neighbour protected area Cuyabeno Wildlife Reserve, thus creating a trans-boundary mega reserve; and finally, *c)*there should be strict and clearly defined no-go zones to oil exploration and exploitation in the core area. Similar conclusions were found by Orta-Martinez and Finer (2007; 2010) for the northern Peruvian Amazon.

Whilst expanding protected areas is of importance, the enforcement of proper conservation within these areas need to be efficient and successful. Currently, hydrocarbon extraction is found on 25% of the natural World Heritage sites worldwide (Osti et al., 2011). This overlap between industry and biodiversity is difficult to manage, moreover when indigenous communities are also present. The outcomes show drastic social changes to the local communities and the ecosystem that they depend on (Jobin, 2003). For instance, the *oil road* created by Maxus Inc. in 1992 penetrates 140Km into the Yasuni National Park and despite the strict controls on road access, the Waorani and Kichwa communities have still been impacted with changes in the distribution and subsistence systems, the most important being the emergence of wild meat markets outside the boundary of the national parks (Suarez et al., 2009). Hence, the presence of the oil and gas extractives is not allowing the conservation of the biological and cultural diversity within the protected area.

The most recent report on the status of protected areas worldwide shows that 15.4% of terrestrial and inland water areas are under protection (Juffe-Bignoli et al., 2014), which quantitatively is close to the 17% target by 2020, established by the CBD (Convention on Biological Diversity) Parties during the COP (Conference of the Parties) in Aichi, back in 2010. This report also highlights the need to include within the protected areas grow the additional parameters of Aichi target 11, which ask to include biodiversity and ecosystem services considerations, as well as being effectively and equitably managed and well-connected to be an integrated system (Juffe-Bignoli et al., 2014). Some more ambitious, but equally realistic, reports show the need and willingness to protect half of the current natural areas in order to effectively protect the existing biodiversity, their habitat and the ecosystem services we all depend on (Mulligan, 2014c; ZSL, 2014).

Currently, there are no global indicators available to evaluate the coverage of ecosystem services within protected areas (Juffe-Bignoli et al., 2014). Many of the efforts towards this research problem have been successful on mapping and evaluating the status of ecosystem services at local level including socio-cultural considerations (Martin-Lopez et al. 2012) and even modelling different socio-economic scenarios around ecosystem services (Swetnam et al., 2011). At global level the mapping has been done at coarse scale and the studies have focused on biodiversity metrics (Jenkins et al., 2013) and extended similar techniques to ecosystem services, looking at protected areas as places of concordance of conservation of biodiversity and sources of ecosystem services (Naidoo et al., 2008). Nevertheless there is still no agreement on a global method that allows for appropriate evaluation of the status of ecosystem services and their sustainability over time within the protected areas (Juffe-Bignoli et al., 2014).

2.11 Conservation Priorities

Conservation priorities have changed radically over time. The first national park in the world was created, in 1872, to preserve and manage the wonders of nature, which Yellowstone offered, and this was directed to the enjoyment of the general public (Sellars, 1997), although several indigenous groups were forced to move out of their ancestral lands due to the concept of protected areas and the conservation priorities at the time (Spence, 2000). The creation of legally protected areas spread around the world, looking to preserve the aesthetic, spiritual, and touristic values of nature, as well as reducing human impact upon them (McNeely et al., 1994). Most natural areas have been historically occupied by indigenous groups and colonist groups, who can play a key role on their conservation and sustainable use, and this should be reflected in the way they are managed in order to effectively conserve them and avoid cultural and biological diversity loss or socio-economical conflicts (Martin-Lopez et al. 2012; Swetnam et al., 2011).

The big international non-governmental organisations (BINGOs) have contributed immensely towards the increase and proper protection of these designated areas, particularly thinking beyond the national boundaries and stablishing the priorities for conservation in the last two decades. These initiatives include;

- **Last of the Wild**, covering the last 10% of the land remaining with no human disturbance, led by the Wildlife Conservation Society (WCS and CIESIN, 2014);
- **Global 200 Ecoregions**, focusing on unique ecosystems around the world that should be conserved due their uniqueness and risk of being lost (Sanderson et al., 2002; WWF, 2014);
- **Important Bird and Biodiversity Areas** (IBAs) developed by BirdLife to highlight via expert advice and data the places of the world of major importance for the protection of bird species and biodiversity;
- **Conservation Hotspots**, which are the 25 unique areas in the world that were found to concentrate above 35% of all vertebrate and plant species, and are under severe human pressure. They only cover 1.4% of the land surface, so the initiative is seen as a *silver-bullet* conservation solution (Myers et al., 2000) and;
- **Key Biodiversity Areas**, which are international important areas for the conservation at the landscape level, protecting all types of biodiversity, but focusing on the most threatened (IUCN, 2014).

All these delphics are the result of extensive work and research from experts in conservation around the world. However, as in many global-scale studies, the lack of data and coarse-resolution may affect and bias the results (Jenkins et al., 2013). They are all working efforts that are channelling funds to promote the conservation of what each initiative has identified as a conservation priority. Overlapping of some of these areas highlights the importance of certain areas, but at the same time indicates that most parts of the world are considered a prioritisation under one or more of these schemes (Brooks et al., 2006), and that there could be some duplication of efforts in some areas (Mace et al.,2000). Improving information quality and resolution of study in the prioritisation process is necessary in order to demand for an effective and equitable distribution of funds.

As it was mentioned above, the 10th Convention of the Parties (COP), held in Aichi, Japan in 2010, agreed on 20 ambitious targets to be achieved by 2020. Target 11 calls for increasing the coverage of effectively protected and ecologically representative areas to 17% of terrestrial and inland waters (and 10% of coastal and marine areas), especially those of importance for conservation of biodiversity and ecosystem services (CBD, 2014). Target 14 is directly connected and requires to enhance the benefits provided by ecosystems and biodiversity, which recommends to restore and safeguard the ecosystems that are providing vital services such as water, food and other benefits towards the livelihood and well-being of the population (COP, 2014). Defining, quantifying and mapping the services that ecosystems provide has been addressed in several approaches (Naidoo et al. 2008; UNEP, 2014), but locating the areas that should be prioritised to maintain these services in concordance with population growth and distribution becomes essential towards the fulfilment of the Aichi targets.

Within the Western Amazon regional level, there are various initiatives and permanent mapping efforts that cover the whole Amazon basin, looking at national and transnational levels and basically targeting at the inventory of protected areas, indigenous territories and the resources (i.e. services) they provide (IBC, 2013; ISA, 2014; RAISG, 2009). These organisations are producing these crucial information and thus establishing conservation priorities for the region.

For instance the *Instituto del Bien Comun*, IBC, has been working for the last 50 years with rural communities in Peru, mapping land-use and natural resources extraction, and looking to enhance community welfare (cultural, social and environmental) and to support sustainable development (IBC, 2013). A sister organisation, *Instituto Socioambiental*, has used maps and techniques of participatory territorial planning in Brazil as a powerful tool to advocate for the rights recognition of people to a healthy environment and access to its benefits (ISA, 2014). Furthermore, the recognised need of collaborative effort in the region led to the establishment of the Amazonian Network of Georeferenced Socio-environmental Information (*Red Amazonica De Information Socioambiental Georreferencidia*, RAISG) in 1996. The main purpose of RAISG is to create a network of organisations to facilitate information dissemination and exchange across the amazon region (RAISG, 2009), and have had success on producing regional information on protected areas, indigenous territories (RAISG, 2012a), and mapping the pressures they are under (RAISG, 2012b), therefore setting the conservation priorities regionally, as well as influencing decision-making processes at the local level (Benavides and Soria, 2009).

Both regional and global approaches have identified different parts and significant portions of the Western Amazon as a priority for conservation, and the information they have produced is the best source to date for stakeholders and decisions makers. Naidoo et al. (2008) found necessary to move beyond an illustrative analysis, and produce an assessment of all relevant ecosystem services at a global scale and adequate resolution (Jenkins et al., 2013), which would make feasible to identify synergies within the prioritised areas and trade-offs of conserving nature or extracting its resources.

2.12 Ecosystem Services in the Millennium Ecosystem Assessment

Ecosystem services are understood as the values, functions and benefits that humans obtain from ecosystems. Thus, the health and condition of an ecosystem is directly related to, and indicative of, the ecosystems ability to produce and deliver services (MA, 2005; Juffe-Bignoli et al., 2014).

A comprehensive assessment of the current status of ecosystem services was long overdue, so the Millennium Ecosystem Assessment (MA) was a much needed answer. It was a long process due to the nature and complexity of the multi-scale study and the need of different types of knowledge working together. It was necessary to consider how an ecosystem produces local, regional or global benefits. Consequently, a multi-scale approach was necessary in order to inform the process of decision making at a local, national and international level. Ultimately, with this information at hand, stakeholders should be able to produce a shared and agreed body of knowledge (MA, 2005). Furthermore, this approach can help towards the proper adoption and enforcement of policies that are derived from a decision-making process that uses these common findings (Fisher et al., 2009).

The MA was carried out as an ecosystem approach endorsed by the CBD to establish a comprehensive scientific baseline on the status of the ecosystem services and their importance for human well-being (MA, 2005). More than a thousand experts from more than 70 countries worked for about four years to develop a holistic report that sets the grounds for further research such as this study. Even though, the MA framework places human well-being at the centre of the ecosystem services concept, it also recognises that ecosystems and biodiversity have an intrinsic value (UNEP, 2014). The latter is important to consider when decisions are made about the use and prioritisation of ecosystem services benefits and the areas in the world that are providing them.

The MA approach categorises ecosystem services depending on their Provisioning, Regulating, Cultural or Supporting benefits (Figure 2-10). The capacity of an ecosystem to provide one or

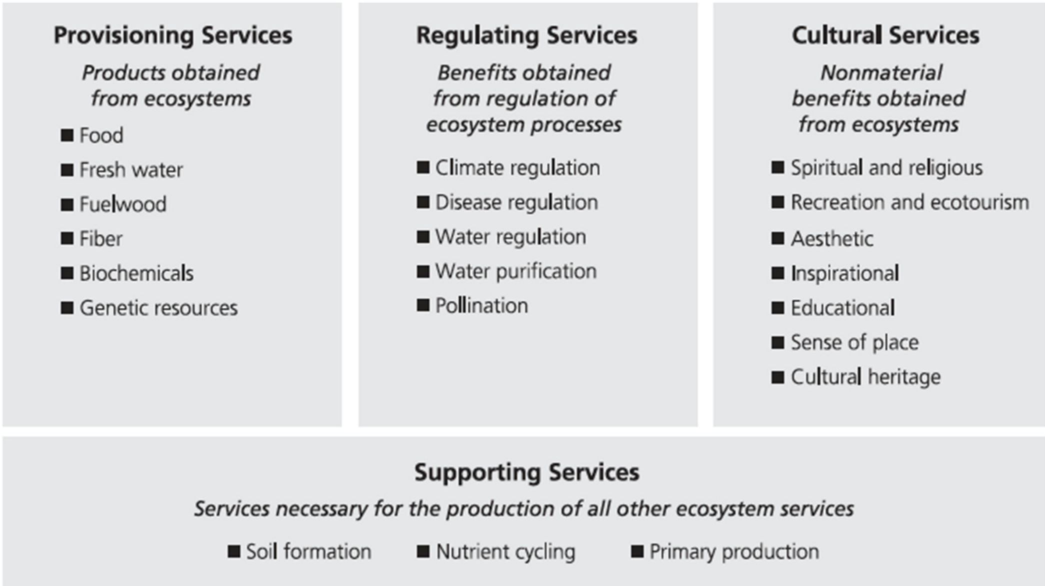

Figure 2-10 Ecosystem Services classification (MA, 2005)

several services depends on its potential to produce and the actual accessibility to the beneficiaries both at local and global levels (Juffe-Bignoli et al., 2014).

Verweij et al. (2009) highlighted the most important ecosystem services within the Amazon, using the MA approach, and attempted to quantify and value them (Figure 2-11). Regulating services of the Amazon include climate regulation, carbon sequestration, fire protection, nutrient retention and hydrological services amongst others. Furthermore, these greatly valued services are strongly influenced by high biodiversity, productive land cover, multiple land use changes and spatially variable desertification (Van Leeuwen et al., 2013).

The MA shows a base path to follow, but along the way there are several research questions that need to be addressed to reach the aspired goals. Carpenter et al., (2006) deconstructed the MA framework to find out that there is a basic need of understanding the link of ecosystems health and human well-being, both at local and global scales. Likewise, it is necessary to have appropriate monitoring tools and indicators to assess the status and change over time of ecosystems and their service provision. Ultimately, relevant scientific information should constitute policy advice and guidance to lead social change and to secure the inclusion of ecosystem services considerations in all strategic development.

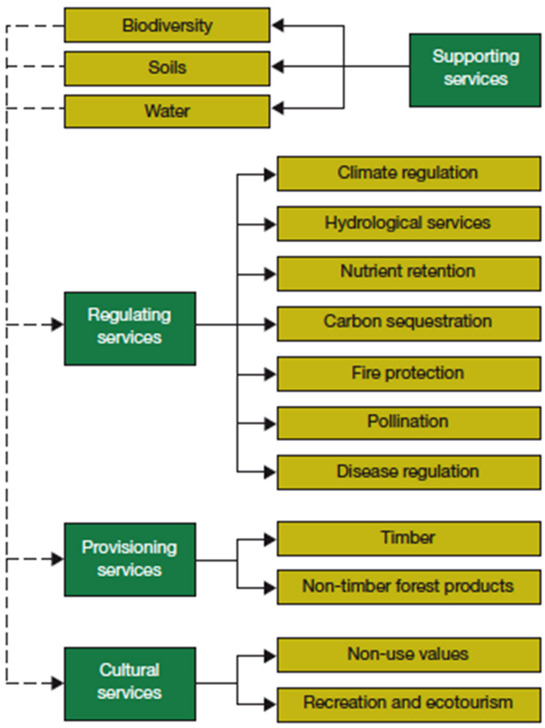

Figure 2-11 Ecosystem services provided by the Amazon as identified by a WWF study, using the MA framework (Verweij et al., 2009)

2.12.1 Provisioning Services

Provisioning services are the most tangible ones, since they are the materials or energy that an ecosystem yields, as exemplified in Figure 2-9. Different ecosystems provide the conditions for proper agriculture, but even marine and freshwater ecosystems can be a source of food. In the same way, raw materials are widely used from forest ecosystems, as well as cultivated species, which then are turned into fuel or energy for anthropogenic activities. (Agrawal et al., 2013). Water provision is a vital service, and many ecosystems play a fundamental role in maintaining a healthy functioning of the hydrological cycle (Aylward et al., 2005). Advancements in biotechnology have produced a vast range of medicinal benefits, which were only possible due to the existence of plants and other components of the biodiversity that contain those raw materials and scientific principles (TEEB, 2013).

2.12.2 Regulating services

The regulating services are not perceptible on a daily basis or at a local scale, but they are definitely of importance in the long term and on a larger scale. The appropriate maintenance of an ecosystem's dynamics provides benefits of sustained local climate and air quality, where trees and forest play an important role of regulation (Joint Research Centre, 2014) Sequestration of greenhouse gases is also of benefit for all living things and it is because of vegetation and soils in the ecosystems that the processes of carbon sequestration and storage are carried out. There is also a role of ecosystem services in moderating extreme events and mitigating potential impacts of natural hazards such as floods, storms, landslides, avalanches, tsunamis, amongst others where the ecosystems provide a protective service of regulation (Smith., 2011). On a local level, regulating services can be seen in the permanent treatment of waste in water and fluids that some ecosystems provide by breaking down the pollutants and even preventing the proliferation of pathogens (Joint Nature Conservation Committee., 2014). In a similar manner, regulating soil erosion and maintaining soil fertility are important benefits from certain ecosystems. Natural pollination by insects, birds and even bats is an important benefit of these biodiversity. In fact, despite technological advances, more than a third of global food crops still depend on animal pollination (Klein et al., 2007).

2.12.3 Cultural services

The cultural services of ecosystems are exclusively for human benefit, since they are non-material and only perceptible as a part of human well-being. Some ecosystems will have spiritual or religious value, others gather educational and knowledge systems used by some societies. Even more, they can be of inspirational or simple aesthetic value, or alternatively influential in societal relations within communities and their sense of place (recognising one's home as one's environment). All of these can be part of an historical cultural heritage value, which many groups can recognise of great importance. Finally, a more palpable service is the recreation and nature-based tourism that ecosystems provide to people for their leisure.

2.12.4 SUPPORTING SERVICES

Supporting services are the basis of the others, since they are the foundation over long periods of time that allowed the formation of ecosystems and cycles that rule them. Consequently, their benefits can only be measured over the long-run, so they are effectively intangible for an individual. However their importance and maintenance are the 'wheels' that keep the other ones moving (MA, 2005). Examples of these services are soil formation, or production of oxygen via photosynthesis, nutrients cycles and the provision of habitats for species to live.

It is important to understand that some ecosystem services may overlap within the prior classification, hence a multi-scale approach can be an effective way to portray all the services in one common space. Moreover, understanding that one ecosystem provides a bundle of services is a first step towards mapping, measuring and understanding its benefits. It is a daunting task to calculate and measure ecosystems services, particularly those of a more subjective nature. However, it is of paramount importance to do it if we are to manage them carefully and thus continue benefiting from them.

2.13 THE ECONOMICS OF ECOSYSTEMS AND BIODIVERSITY APPROACH

The Economics of Ecosystems and Biodiversity, TEEB, is a global study of the economic importance of biodiversity and ecosystems, highlighting the cost of the loss and degradation of these natural systems. By bringing together expertise from a mixture of fields including economics, science and policy to help create practical actions (Ring et al., 2010). Whilst the MA is a conceptual framework to understand the impact of environmental degradation on human well-being and the natural world, Ring et al. (2010) argues that the MA lacks information regarding the dynamics of social-ecological systems and the complex relationship between human well-being and ecosystem services.

A major reason why environmental degradation has occurred on such a vast scale is that the price of the natural environment is not taken in consideration during economic decision making (Balmford et al., 2002). TEEB is designed not for the academic or conservationist who understands the value of nature, but instead for the public administrator or businessman, to help them become aware that the current calculations in regards to the harnessing products from natural environment do not add up, and by not including the environment into the calculation creates a false economy (Kumar and Martinez-Alier, 2011). The markets should include environmental services and its products, with the increasing price to be felt by the consumer (Kumar and Martinez-Alier, 2011).

In terms of TEEB and the Amazon, there has been an emphasis on this region due to its role in carbon storage and capture, high levels of biodiversity and for it being a 'water pump' for a vast area outside of the Amazon (Kumar and Martinez-Alier, 2011). TEEB helps communicate and explain the Amazon's importance which can be understood by academic ecologists but also by actors in the business world as well as policy makers. It is estimated that pristine rainforests are worth on average $6,120 USD per hectare per year due to the full potential of biodiversity benefits (TEEB, 2013). Although some studies suggest that restoration of degraded rainforest can regain up to 80% of original biodiversity in 50 years, this process does not include the specialist species that may be lost during that process (Dent and Wright, 2009; Sberze et al., 2010)

2.14 Ecosystem Services in the Western Amazon

The most relevant ecosystem services that have been studied globally (Naidoo et al., 2008) and their value assessed (Costanza et al., 1998) include: carbon stock and sequestration, water provision (Larsen et al., 2012), hazard mitigation and, more recently, nature-based tourism

(Balmford et al., 2009). It is understood other services are being provided by the ecosystems, such as the use of food provision, medicinal resources, biological pest-control, and pollination, amongst many other relevant at local and site scales. This study focuses on the more regional and global benefits of the formerly mentioned services.

2.14.1 Carbon Services

At a global level, tropical forests annually cycle approximately 8% of the atmospheric carbon, holding 40% (428 Pg) of all terrestrial carbon (approximately 58% in forests and 42% in soil) through the chemical processes of photosynthesis, respiration, decomposition and litter accumulation (Meister et al., 2012), making them vital to the global carbon cycle. Protected areas within tropical forests contain approximately 70.3 (Pg C) in biomass and soil within humid tropical forests equivalent to 3.5% of global terrestrial stocks (Scharlemann et al., 2010). Furthermore, tropical intact forests are a sink within the global carbon budget, with an average of 1.2 Pg C per year during the last two decades, which places them above both temperate and boreal forests together (Pan et al., 2011) and confirms their importance at global level. Moreover, the pressure of deforestation caused a release of 0.5 Pg C per year during the 1990s (Malhi et al., 2011) and even though it decreased in the last decade due to Brazil's success on controlling deforestation and effectively managing forest logging, it is back on the rise (Imazon, 2014; Lang, 2014). Forest carbon is stored in the form of live biomass (above and below ground): above ground biomass (AGB) is defined and accumulated in the standing woody tissues of vegetation (Saatchi et al., 2011). Approximately 50% of the dry weight or biomass of tropical vegetation is carbon (Covey et al., 2012); and below ground biomass (BGB) is defined as the carbon stored underground within the organic soil matter in roots, usually up to 1m of depth (Scharlemann et al., 2010).

At the regional level, it is estimated that a quarter of the global terrestrial carbon is stored within the Amazon, with a sequestration rates of 0.6 Pg C per year (Baker et al., 2004). Tropical forests in the Amazon are currently a carbon sink, since they uptakes approximately 0.8 Pg C per year through regrowth, which is slightly (0.4%) higher than the carbon lost due to emissions from deforestation and tree mortality (Pan et al., 2011; Philips et al., 2008). The relationship between aboveground and belowground biomass are inversely related when comparing Eastern and Western Amazon (Mitchard et al., 2014). Furthermore, the Western Amazon is in comparison more fertile in terms of plan species due to soil, climate and seasonal characteristics (Baker et al., 2004; Malhi et al., 2011).

At a more local level, in Ecuador, the Yasuni-ITT initiative (detailed in section 2.6) was based on the agreement of the Ecuadorian government to maintain the 850 million barrels (135 Mm^3) of untapped oil reserves, in exchange for half the opportunity cost of exploiting the oil. In terms of carbon, the extracted oil would cause emissions of 0.4 Pg of CO_2, which is currently estimated to cost USD7.2 billion within the Carbon Market (Larrea, 2010; Rival, in press) Even though the ITT block represents a small area amongst the rest of oil concessions in the Western Amazon, the area is unique in terms of its cultural and biological diversity (Bass et al., 2010; Pappalardo et al., 2013). If successful, this initiative would have been an example that could have potentially be adopted by the neighbouring countries. Nevertheless, the demand for oil crude and derivatives has only increased in the last decades (OPEC, 2013), so keeping these comparatively *small* reserves untapped in one area will turn into further pressure on another area, in order to keep up with increasing demands worlwide (Butt et al., 2013). Even more, maintaining the oil underground over a long period of time will be very dependent on both the global prices of oil, and how much investment the countries and extractive companies are willing to devote for exploiting those resources. Consequently, an actual sustainable approach should aim to decrease the dependency on fossil fuels at local and global levels, and only then the pressure over these natural areas will ease.

In summary, all relevant studies show the importance of the carbon services of the Amazon, particularly ther western region, both regionally and globally. This service alone should be enough reason to direct funds and efforts for its effective consevration (, which additionaly includes biodiversity protection and maitenance of other relevant ecosystem services (Malhi et al., 2008; Pan et al., 2011)

2.14.2 WATER RELATED SERVICES

One of the major and long-lasting impacts of oil contamination has been observed on water resources, especially because both water quantity and quality are affected by land use change and contamination respectively (van Soesbergen and Mulligan, 2013). For instance, the contamination of Texaco in Ecuador (section 2.5.2) was estimated at USD 27 billion to recover the polluted groundwater in the region (Amazon Watch, 2009). Furthermore, local people in the whole Western Amazon depend directly on sources of clean water that comes from rivers and groundwater sources, as well as rainfall water collection, particularly in areas where oil pollution has occurred (UNICEF, 2009). Few have access to treated water, and the provision of drinking water has been recognised as a priority in the oil-impacted areas, so the ecosystem services that maintain the water supply, including seasonal variations, should be understood and preserved.

The Amazon waters are used for hydropower and other economic purposes, thus the number of existing and planned hydroelectric dams ascend to 417, distributed unevenly and with high concentrations of future projects in the Andean reach of the Amazon in Peru (RAISG, 2012b). The operation of these dams depends in part of the management of land in the upstream areas. The regulation of water balance and river flow are water services that can only be sustain if the whole ecosystem is kept healthy and functioning (Foley et al., 2007). Considering that nearly 80% of the population globally is under some level of threat to their water security, it becomes vital to evaluate the risks of harming and impairing these provisioning services (Vorosmarty et al., 2010). More importantly, research efforts have already been directed towards understanding the consequences of drought events in the Amazon (Lewis et al., 2010) and their potential to become extreme events with the effects of climate change in the near future (Malhi et al., 2008). Water resources development (i.e. dam density, river fragmentation, human and agricultural water stress, flow disruption, industrial use) is the highest threat to water security worldwide (Vorosmarty et al., 2010), and within the Amazon basin the hydroelectric dams, alongside oil and gas, and mining development are at the top of the list of threats to water services (RAISG, 2012b)

2.14.3 NATURE-BASED TOURISM

Global trends on nature-based tourism show that there is a disconnection with nature and its relation with the surrounding ecosystems, particularly in developed and developing countries, where more than half of the population live in urban areas (UN, 2014). Nature-related tourism can provide *a)* funding for conservation of areas of importance to biodiversity and ecosystem services and *b)* heighten positive attitude towards the environment and *c)* create awareness about the importance of all nature components and ultimately political will to preserve the benefits people received from ecosystems (Balmford et al., 2009; Kuenzi and McNeely, 2008). Latin American countries have increased number of visits to natural areas over the last two decades, mostly from international visitors, and their contribution to the national GDP is considered to be of importance (Balmford et al., 2009). Protected areas both governmental and private are the main destination for nature-based tourism, and national governments tend to favour their protection as long as they are not in conflict with other economic interests (Juffe-Bignoli et al., 2014). Mapping these services at a global scale has been done with some clever programming and using publicly available data of photos and location of urban areas to develop a map of interesting remote touristic attractions (Heinla, 2010)

At the local level, local communities have found in ecotourism an alternative to the exploitation and degradation of their non-renewable resources. For instance, nature-based tourism has become the main source of funds for small communities, such as Sani Isla in Ecuador, where the local Kichwa community currently manages a self-sufficient eco-lodge that even funds some community projects on education, agriculture and handicrafts trading (Sani, 2008). Similar initiatives are found all over the protected areas of the Amazonia in Ecuador and Peru, and are supported by the relevant government agencies (MAE, 2014; SERNANP, 2014) Nevertheless, the revenue they provide to the national economies does not compare with the oil and gas revenues, and where those two are in conflict, the scales tends to tip towards the most profitable option (e.g. oil and gas extraction). Larsen et al. (2012) research shows that identifying and conserving critical sites of nature yields high benefits when considering the ecosystem services included. Consequently, properly mapping nature-based ecosystem services and visually joining them with other relevant benefits can help tipping the scales in favour of conserving biodiversity and maintaining all the ecosystem services nature is providing.

CHAPTER 3

MULTICRITERIA GIS ANALYSIS AND GEO-VISUALISATION OF THE OVERLAP OF OIL IMPACTS AND ECOSYSTEM SERVICES IN THE WESTERN AMAZON

3.1 OVERVIEW

This chapter consists of the published paper that was the product of this part of the research. The manuscript is presented below, whilst the published paper can be found in Appendix B, as well as supplementary material in Appendix C. The objective of this research was to determine the extent of oil and gas historical activities in relation to ecosystem services and other relevant environmental variables at the regional level of the Western Amazon, using a combination of collected experts' opinions and remotely sensed data. The paper builds upon previous research that overlaid oil and gas concessions with biodiversity, protected areas and indigenous territories data to show the mosaic of conflicts (Finer et al., 2008). It aims to include both oil and gas impacts on top of potential ecosystem services in a bivariate space and scale. It begins with an introduction to the topic retaking on some of the main issues already covered. It uses a multicriteria analysis embedded into GIS techniques to ultimately produce informative indices of oil and gas impacts, ecosystem services and risk of ecosystem services loss. These results constitute a baseline to be used and compared with other approaches, such as the modelling tools utilised in the next chapters.

Multicriteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon

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Multicriteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon

Abstract

Oil extraction operations can be found in all types of environment, including the most threatened and delicate tropical rainforests. The Western Amazon has been widely recognised for its biodiversity and important ecosystem services, but it is also rich in oil reserves. The governments of Colombia, Ecuador and Peru have been increasingly developing and exploiting oil resources in these remote areas and this exploitation is an important contribution to their national economies. This analysis aims to inform a more sustainable development of extractives in the region using innovative techniques of geo-visualisation. The results yield a comprehensive oil impact assessment for the region, and then highlight environmentally important zones, to finally visualise areas of significant environmental risk based on future planned oil developments. The maps show that areas most affected by oil activities, such as the Yasuni National Park, in Ecuador, and the Corrientes River Basin, in Peru, are also the source of ecosystem services, and furthermore, areas, as the Manu National Park, in Peru, are in risk of losing their ecosystem services value due to oil development expected in the near future. A better understanding of the situation supported by scientific information and innovative geo-visualisation will help to put in place and enforce policies and thus minimise the socio-environmental impacts of the activity while maintaining the production of oil and associated revenue that is vital for the region's economy.

1. Introduction

Oil exploration in Ecuador, Peru and Colombia started in the early 1900s, in the Gulf of Guayaquil, Ecuador, the area of Talara, in the northern coast of Peru, and the Magdalena River Basin in Colombia (Hanratty, 1991; Hudson, 1992). The oil industry is capable of generating significant revenues, especially at times of high demand, but it equally needs considerable investment, especially when working in isolated and remote areas (Ramos and Veiga, 2011). The infrastructure and activities required for oil exploitation traditionally include roads, wells, pipeline installations and construction of large production facilities (Baynard, 2011). The impacts of all these infrastructures are of great concern when they are built in delicate and important areas for conservation, and the provision of ecosystem services.

The national oil company in Colombia, Ecopetrol, is in control of a large pipeline system that covers a significant part of the centre and north of the country, and, in minor extent, in the southern border (ECOPETROL, 2010). In Ecuador, the Trans Ecuadorian Pipeline, SOTE, and the OCP, Heavy Oil Pipeline, are the main oil infrastructures that carry oil across the Andes (Mirabik, 1991; Lucero, 1997). The oil and gas industries in Peru have constructed two major pipelines to extract resources from the Amazon all the way to the Pacific Coast, for export and internal supply (PERUPETRO, 2010). There are several development projects, some already underway, that aim to expand the extraction of resources, particularly towards less-explored areas in the Amazon (Presidency of Ecuador, 2012).

On the other hand, the Western Amazon has been widely recognised for its high species richness and endemism. In fact, 20% of the Western Amazon territories are under some type of protection due to the encompassed biodiversity. Even more, there are more than a thousand indigenous territories (Bass et al., 2010; RAISG, 2009; Finer et al., 2008; Lucero, 1997). One of the major impacts of oil contamination is on water resources. It is estimated, as part of the Texaco lawsuit in Ecuador, that it would cost some USD 27 billion to clean-up the polluted groundwater in the affected region (Amazon Watch, 2009). Furthermore, local people in the whole Western Amazon depend on sources of clean water, that come from riverbeds and groundwater sources, as well as rainfall water collection, particularly in the areas where oil pollution has been significant (UNICEF, 2009). The provision of ecosystem services has been recognised as a priority in the oil-impacted areas (Ojeda et al., 2008; Bastian et al., in press), thus scientific information would help to better maintain their supply.

The aim of this study is to provide information for a more sustainable development of extractives in the Western Amazon by highlighting the ecosystem service impacts of oil developments and using innovative GIS techniques to visualise and understand the risks and propose an optimal extraction and distribution strategies with lower socio-environmental impacts. To achieve this aim, firstly, the construction of a comprehensive geographic database with all variables involved was set as an objective. On a second stage, the development of new techniques of geo-visualisation is set as a target, in order to better represent and analyse focus areas.

2. METHODS

The Western Amazon comprises areas of Colombia, Ecuador, Peru, Bolivia, Venezuela and Brazil. Geographically, our study area lies within the coordinates of latitude 10°N to 20°S, and 80°W to 60°W of longitude. Even though the GIS was developed and applied over the whole area, the focus of the analysis is on the Amazon of Colombia, Ecuador and Peru, due to similarities in both the ecosystem services and history of oil industry in these countries (Finer et al., 2008). An extensive research on publicly available data was completed. Data from official and governmental sources were combined with publicly available data from private (i.e. oil companies) and civil (i.e. NGOs) sectors, in order to build a comprehensive geographic database. The collected datasets include data for oil blocks, pipelines, wells, waste pits, stations, flares, as well as roads, local communities, and river networks. Additional information on environmental variables (elevation, water balance, land cover, local drainage direction, and watersheds) as well as social variables (administrative boundaries, urban areas, land use) was derived and merged from the SimTerra database (Mulligan, 2010a). Data research and gathering was exhaustive to assure that all the used variables cover the entire focus area. The pioneering way to compile all the available information into a consistent geographic database, was achieved by keeping a simple raster format, obtained with the Inverse Distance Weighing deterministic method for multivariate interpolation (ESRI, 2011), maintaining a constant resolution, and built-in rules with the purpose of ease of update when additional data are included. Only when data was available for the whole focus area, was it included in the analysis to maintain consistency in the weighting and results. More detailed information on the datasets included in the analysis is presented in Table 1. Thus, all data were pre-processed and, when necessary, rasterised to match a common resolution of 1 km per pixel. ArcGIS (v.10.0; ESRI, 2011), PCRaster (v.Nov.2009; Utrecht University, 2009), and R (v.2.15.2; R, 2008) software packages were used for data management, geo-visualisation and analysis.

Table 1. List of variables used for the GIS multi-criteria analysis of the oil activities impacts and ecosystems services provision in the Western Amazon.

variable	source of information	data type	Units
Oil pipelines	(PETROECUADOR, 2010; ECOPETROL, 2010; PERUPETRO, 2010; EquitableOrigin, 2011; UNIGIS, 2010)	polyline	Km
Oil wells*	(UNIGIS, 2010; Agencia Nacional de Hidrocarburos, 2012)	point	
Block - concessions	(Jenkins, 2009; Agencia Nacional de Hidrocarburos, 2012; IBC, 2009)	polygon	Km^2
Elevation	(Farr and Kobrick, 2000)	raster	m(a.s.l)
Roads	(FAO-GIEWS, 2008)	raster	pixels
Urban areas	(CIESIN et al., 2004)	raster	classes
Amphibians spp. Richness	(Mulligan, 2010a using (IUCN et al., 2008b)	raster	# spp.
Birds spp. richness	(Mulligan, 2010a)	raster	# spp.
Mammals spp. Richness	(Mulligan, 2010a using (IUCN et al., 2008a)	raster	# spp.
Reptiles spp. Richness	(Mulligan, 2010a using (IUCN, 2010)	raster	# spp.
Protected Areas	(UNEP-WCMC, 2009)	raster	unique ID
Tree coverage	(Hansen et al., 2006)	raster	fraction
Carbon Stock	(Ruesch and Gibbs, 2008)	raster	tonnes/Km^2
Local water balance	(Hijmans et al., 2005; Mulligan and Rubiano, 2010)	raster	mm/year

* *in Colombia, the mapped wells are currently not in exploitation within the area of study*

Due to the large range of factors that determine the impact of oil activities in terrestrial environments, the most effective method to analyse variables of diverse units is a multi-criteria analysis (Boroushaki and Malczewski, 2010). First, a comprehensive analysis of the current oil infrastructure was performed with all the relevant variables to determine the extent of the oil impact in an index. Second, biological and physical variables were combined to determine an ecosystem services index by examination of the potential (i.e. provided but not necessarily used) ecosystem services (Mulligan et al., 2010). These services are calculated locally for every cell of analysis. Finally, the resulting oil impact and ecosystem services indices are brought together within a bivariate geo-visualisation, in order to identify areas of high and low risk of significant ecosystem service loss.

For the oil impact index, it is stated that the main impacts are on-site infrastructure (Baynard, 2011, Goosem, 2004), thus they were given a higher weight of impact. However, off-site effects can also be of noticeable impact, hence an influence area of the infrastructure is assigned to the neighbouring pixels for this index. Major oil infrastructures (i.e. pipelines and oil wells) are assumed to be the main causes of impact of the oil industry, and occur on point sites. Roads built and maintained by the oil activities are the drivers of urban development and deforestation, hence also included, and properly weighed, as described below. In terms of the ecosystem services index, there were several assumptions and considerations to make. All biodiversity variables were included as number of threatened species, due to the intrinsic value of biological diversity within an ecosystem (Eichner and Pethig, 2009). Secondly, protected areas are included as Boolean maps since they are, by definition, environmentally important zones where the human impact is null or at least controlled to be at its minimum. Third, tree coverage (as a percentage) and carbon stock (in tonnes/Km^2), help to identify the areas where deforestation processes have not taken place and carbon storage services are of great potential value. Finally, water services are assumed to be locally represented by water balance data (in mm/year), which was calculated using the FIESTA hydrological model (Mulligan and Burke, 2005), resulting in the water available for use at the surface.

The weighting of criteria for the analysis was done by adopting the ratio estimation method (Malczewski, 2004). Initially all variables for oil impact (oil pipelines, oil wells, oil concessions, roads and urban areas) were ranked from 1 to *n* in order of their relative weight or impact (i.e.

in relation with the other considered variables), assigning 1 to the variable of highest impact and *n* to the lowest. The ecosystem services variables (threatened species of amphibians, birds, mammals and reptiles, protected areas, tree coverage, carbon stock, and water balance) were ranked in the same way in a second group of criteria. Then, for each criterion within both groups, a fractional value *fr* is assigned according to the absolute impact of the variable within the pixel ($1 < fr < 100$). In the next step, a ratio *r* is derived by dividing every fractional value by the maximum fraction value amongst the group (Equation 1)

Equation 1

$$\boldsymbol{r_i = \frac{fr_i}{\max fr_{i-n}}}$$

where fr_i is the fraction of a variable *i*, and $\max fr_{i\text{-}n}$ corresponds to the maximum value within the range of the variable. From this point, an initial weight value is calculated by dividing each ratio by the rank score (Equation 2).

Equation 2

$$\boldsymbol{w_i = \frac{r_i}{\mathrm{rank}_i}}$$

where w_i is the weight for a variable *i*, r_i is its ratio and rank_i corresponds to the assigned rank for the variable. Finally, a normalised weight ($0.00 < w_Z < 1.00$) is calculated for each criterion dividing it by the sum of weights (Equation 3).

Equation 3

$$\boldsymbol{w_Z = \frac{r_i}{\sum w_i}}$$

where w_Z is the final normalised weight for a variable *i*. For the analysis of the oil impact index, an additional measure was included, aiming to show the influence that a particular feature (e.g. oil pipelines, oil wells) has within or around the pixel that it occupies. In the ecosystem services, similar variables were given equal rank and then weighted using the described method (Table 2). The spatial neighbourhood of influence used for the oil impact index (Table 2, last column) is independent from the weighting process, and was assigned according to expert advice (Larrea, M. *pers. comm.*). The influence is defined by the circular neighbourhood of ratio equal to the number of influencing pixels, and, in the case of oil wells, multiplied by the total of individual wells found within that pixel.

Table 2. List of variables and weight calculation for the analysis of the oil impacts and ecosystem services in the Western Amazon.

OIL IMPACT	rank	fraction	ratio	weight	normalised weight	influence (pixel)
Oil pipelines	2	100	1	2	0.27	2
Oil wells	1	100	1	4	0.54	3*x**
Block - concessions	3	50	0.5	0.67	0.09	1
Roads	4	50	0.5	0.5	0.07	2
Urban areas	5	25	0.25	0.2	0.03	1
			TOTAL	7.37	1	
ECOSYSTEM SERVICES						
Threatened spp. amphibians	3	10	0.1	0.03	0.02	
Threatened spp. birds	3	10	0.1	0.03	0.02	
Threatened spp. mammals	3	10	0.1	0.03	0.02	
Threatened spp. reptiles	3	10	0.1	0.03	0.02	
Protected Areas	3	10	0.1	0.03	0.02	
Tree coverage	2	35	0.35	0.18	0.12	
Carbon Stock	2	35	0.35	0.18	0.12	
Water Balance	1	100	1	1	0.66	
			TOTAL	1.52	1	

** The influence within the pixel was multiplied by the number (x) of wells mapped within the cell*

Using the normalised weights, a raster map was derived by interpolation for every variable. Then they were all added into a resultant map that represents each index, from 0 (lowest) to 1 (highest). In a final stage, a script brings together both indices, oil impact and ecosystem services, and allows their geo-visualisation in a bivariate map. For this, each dataset was divided in ten data bins using as break points the Jenks Optimisation Method (ESRI 2011), and excluding the values of zero since they skewed the histogram and data breaks, and allowing to represent the clusters of classes within both datasets. Using the bin information, a choropleth colour scale was derived using the RGB colour model, where two variables can be represented within a bi-dimensional space (after Holland, R. unpublished code). Then, the spatial information of every cell is added to the code, in order to represent them within the appropriate geographic coordinates. The automatized script delivers a final bivariate map, which represents the risk of significant ecosystem services loss.

3. RESULTS

A total of 1678 oil wells were mapped in the Western Amazon, including Ecuador (59%), Peru (38%), and in very minor extent in Colombia (3%). The major pipelines in the studied countries cover an extension of 11,185 Km, since they all cross mainly from East to West across the Andes towards the Pacific Coast. From this total of major pipelines, 30% lies over the Western Amazon, crossing major rivers along their way. Additionally, a considerable network of secondary distribution pipelines of smaller diameter is known to be present in the area, although they were not included in this study. The road network in the Western Amazon totals 30,483 Km, mainly secondary roads, which are a major cause of habitat fragmentation. The oil blocks in the Western Amazon cover an area of 657,000 Km^2, and this corresponds to 74% of the Peruvian Amazon, 65% of the Ecuadorian Amazon, and only 4% of the Colombian portion of the Amazon.

The resulting oil impact index (Fig. 1) shows major impacts on the Ecuadorian Amazon, particularly in the northern areas, which validates the index, since most of the oil development has taken place in these zones during the last 44 years. The impact is equally high on the Corrientes River area in Peru, where there has been oil extraction for the past four decades. In the Colombian Amazon, the impacts are less significant due to the lower oil development in the area, which is used as a control area. High values are also observed along the path of the major pipelines. Statistically, the data distribution shows that up to the third quantile, values are close to 0 (mean=0.03), and the top 10% of the values (max=0.91) are due to high on-site localised impacts.

Focusing on the resulting maps of ecosystem services index, high numbers of species are concentrated across the whole Western Amazon. Particularly, the highest values for threatened amphibians (up to 133 spp./Km^2) are found in the Yasuni area in Ecuador and the conservation area of Imiria in Peru. Bird species numbers show even higher values in the lower Eastern Andes of Ecuador (735 spp./Km^2) and the Pacaya-Samiria area in north-eastern Peru. For threatened mammals, there is high concentration in the Manu National Park in south-eastern Peru (200 spp./Km^2) and across the lower Andes all the way up to the Amazonas Department in southern Colombia. These values are consistent with the literature (Bass et al., 2010). The protected areas account for a total of 2.3×10^6 Km^2, which represent 26% of the total area of study, although the bigger areas are actually located on the extensive Amazon portion of Brazil.

Analysing the ecosystem services map (Figure 2), the whole Western Amazon holds great importance with high values (above 0.5) particularly within protected areas, due to their high levels of carbon storage and commonly positive water balance, assumed to be the source of good quality drinking water. When looking at the levels of importance, in Ecuador, the Yasuni

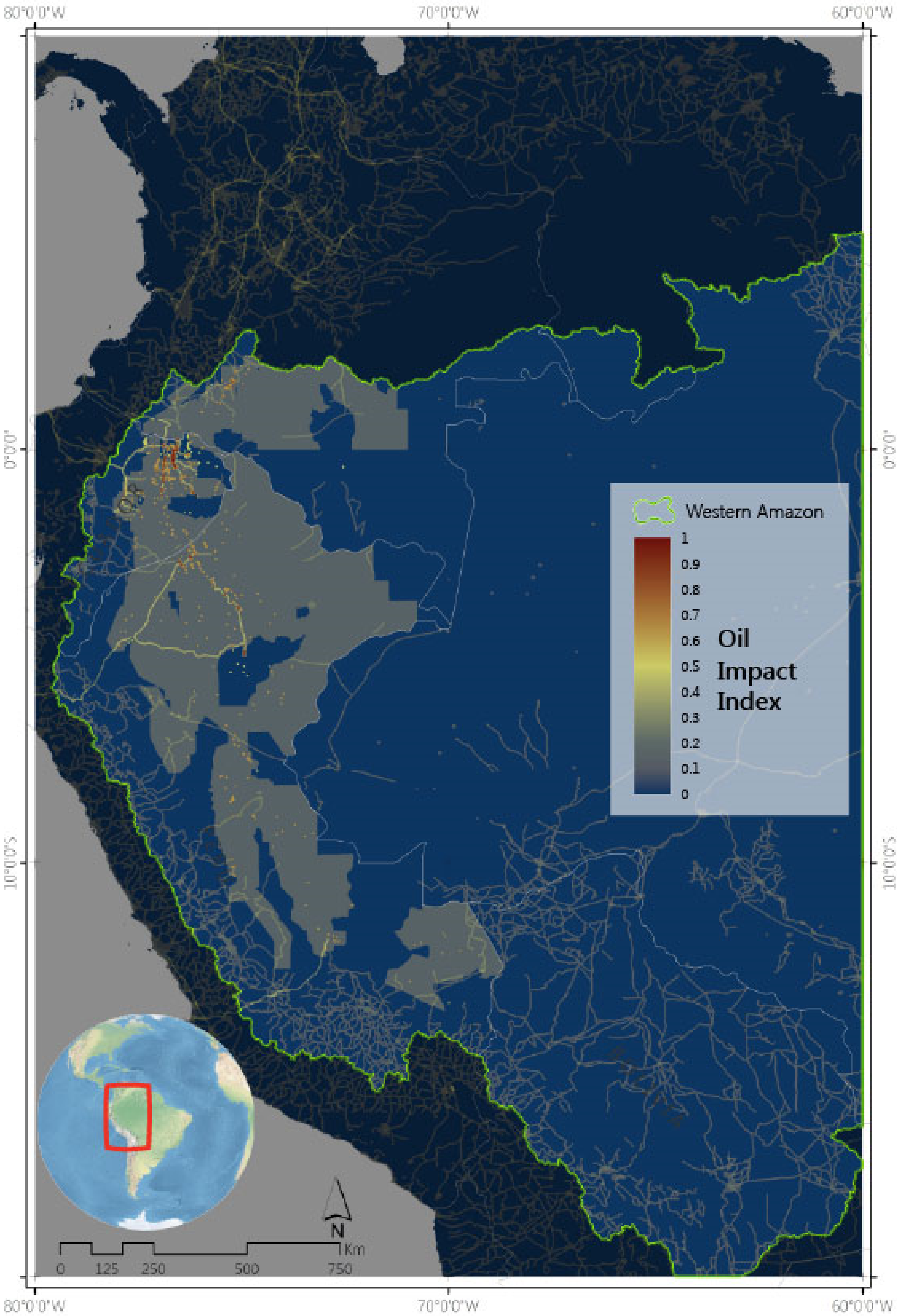

Figure 1. Oil impact index (0-1) for the Western Amazon, at 1 Km resolution

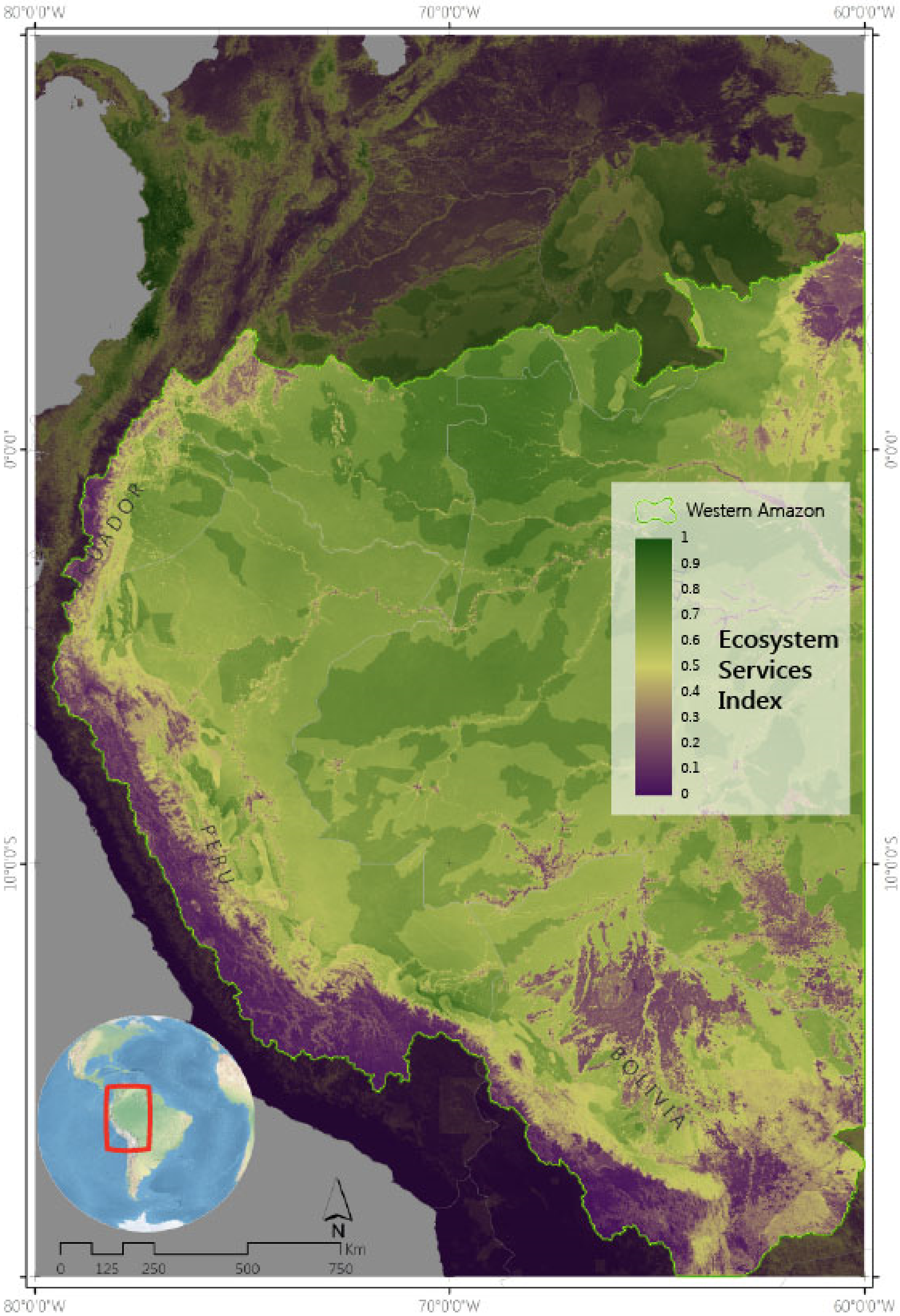

Figure 2. Ecosystem services index (0-1) for the Western Amazon, at 1 Km resolution

National Park and small portion of the Cuyabeno Reserve in the north are of high importance. Equally important are the areas of Pacaya-Samiria National Reserve as well as Manu National Park in Peru. Statistically, the data show a bimodal distribution with a third quantile of 0.44 and a maximum value of 0.75 in areas where all ecosystem services are high.

When combining both indices and visualising them in a bivariate map, the areas of north-eastern Ecuador and north Peru show higher levels in both oil impact and ecosystem services indices (Figure 3). This can be expected as the oil facilities and infrastructure were located in the middle of the rainforest areas, which have been recognised to contain high biodiversity levels (Bass et al., 2010) and proven to be the source of ecosystem services (Ojeda et al., 2008; Mulligan, 2010a). Even more important is to look at the areas with high levels of ecosystem services (above the third quantile) and in the medium range of the oil impact index, which are areas that have not been "oil developed", but that are included in plans of future developments. These areas clearly could have a high risk of ecosystem service loss, and in general they coincide with protected areas and indigenous territories that overlap with oil concessions.

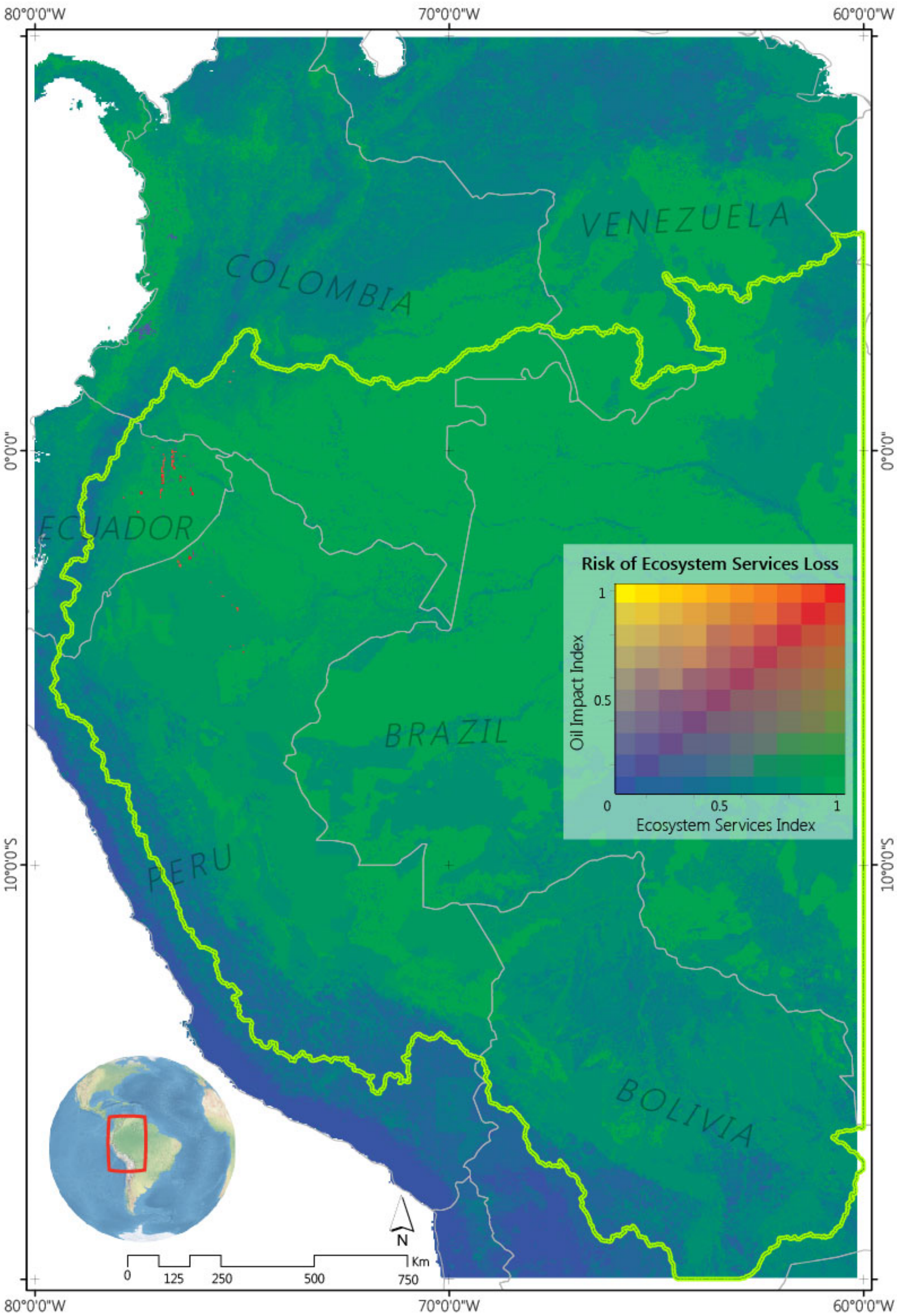

Figure 3. Risk of ecosystem services loss (0-1) obtained combining, in a bivariate space and scale, oil impact and ecosystem services indices, for the Western Amazon, at 1 Km resolution

4. Discussion and Conclusion

A comprehensive GIS analysis of oil infrastructure, potential for impact and environmental importance has not been performed in such detail for the whole of the Western Amazon. Finer et al. (2009) successfully described the oil situation by mapping the oil concessions, but further and more detailed work was needed to evaluate the actual extent of the impact. Furthermore, identifying areas of risk of ecosystem service loss due to oil activities is a step forward towards a cleaner and more environmentally sound extraction of resources. The multi-criteria analysis performed shows the impacts of oil infrastructure in detail, and then combines them with some of the ecosystem services that these same areas provide. The resulting maps were discussed with experts from both the environmental and industry fields, and there is a general agreement on the extent of impact and the importance of the potential ecosystem services that the areas hold.

As a regional study, the information produced can help to better understand the current trans-national situation of oil in the region beyond the official reports from the environmental agencies in each country. Additionally, the reliability of the indices is supported by objective and independent scientific data. Consequently, the results can effectively be of use and application on informed decision and policy making. Open and public information may be of use and support to all stakeholders, from oil companies, local governments, civil organisations through to indigenous communities living and depending on the land, its resources and its ecosystem services.

This information can only be effective if it empowers decision makers, and helps them in the process of informed decisions and better planning of future development. Currently, Ecuador and Peru are signing agreements to extend the oil frontier across their borders by integrating the North-Peruvian pipeline with the oil concessions to be exploited in South-eastern Ecuador

(Presidency of Ecuador, 2012). For these reasons, the need for independent sources of scientific information is greater.

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NOTE: the published version of this paper and supplementary material for this chapter can be found in Appendix B and C, respectively.

CHAPTER 4

EVALUATING DIFFERENT STRATEGIES FOR CONSERVATION PRIORITISATION IN THE WESTERN AMAZON

4.1 OVERVIEW

Within this chapter the research focuses on conservation prioritisation in the Western Amazon (WA). It starts by naming the two main tools to map ecosystem service and it compares them with the tool proposed for this study. Then, it describes in detail the relevant parameters that were included in the analysis of different strategies for conservation prioritisation, looking at the importance of ecosystem services, conservation of biodiversity, and pressure and threat from extractives, in separate potential scenarios. Conservation prioritisation is understood as a partly subjective process that involves value judgements on which elements of ecosystems and biodiversity are worth preserving. Identifying areas of consistent of high priority under a range of possible metrics would produce a more scientific, objective, and insightful approach to prioritising conservation and future developments.

4.2 MAPPING TOOLS FOR ECOSYSTEM SERVICES

Conservation of biodiversity and sustainable use of natural resources have been on international agendas, as a major concern, since 1992, when the Convention on Biological Diversity, CBD, was outlined to help formalising at international level the conservation of biodiversity and the sustainable use of its components in the environment (CBD, 1992). The CBD brought to the world's attention the changes and impacts that humankind causes on the environment. There were consideration of economics of the environment and resources sustainability, considered as natural capital (Costanza et al., 1998), but this was not transformed into policy. Understanding the key role of ecosystems in human well-being and place them as a scientific priority as well as a policy driver was one of the major achievements of the Millennium Ecosystem Assessment (Carpenter et al., 2009) and it triggered a new research field dedicated to find them in the map (Brooks et al., 2006; Naidoo et al., 2008).

Mapping ecosystem services within projects and case studies (e.g. oil and gas infrastructure planning) are usually focused at the local level and based upon data collected in the field, providing valid and useful information for the specific purpose of the study (Aleman et al., 2008; ENTRIX, 2001). Often, these datasets are neither consistent, nor comparable between different sites, so the same approach is not easily applicable elsewhere (Joint Research Centre, 2014; Smith, 2011). On the other hand, global assessments are commonly based on remote sensed data and usually done at coarse scale (Naidoo 2008; Soares-Filho et al. 2006), thus reliable at regional or global scales, but not applicable to processes on-the-ground (Josse et al., 2013). Despite it all, there are several efforts to develop tools to map, measure and value ecosystem services at several scales and levels of specificity (Bagstad et al., 2013; Crossman et al., 2013). Given the complexity of the factors involved, it is a rather difficult task to include them all in one functional computer model that represents the state and behaviour of ecosystems. Furthermore, relevant data are often scarce, so there is a balance between complexity and efficiency to parameterise a model (Waage et al., 2011).

Amongst the tools that have been developed with the purpose of mapping ecosystem services at a national or regional scale, the two major and widely recognised approaches are InVEST from the Natural Capital project (Tallis et al., 2013) and ARIES (Villa et al., 2009). These tools have contributed immensely to the field of mapping ecosystem services, and have been applied with success in studies worldwide (Bagstad et al., 2013; Goldstein et al., 2012; Daily et al., 2013; McKenzie et al., 2014; Mushet et al., 2014; Reyers et al., 2014). A comparatively new tool, Co$ting Nature (Mulligan 2012b) was used for this current research. Nevertheless, the three tools are firstly compared. The main characteristics of each of these tools is summarised in Table 4-1, and then described in the following sections.

Table 4-1 Comparison of mapping tools of ecosystem services.

Comparison parameters	**Ecosystem Services Tools**		
	ARIES v.*alpha*	InVEST v.2.5.6	Co$ting Nature v.2.45
ES relevant outputs	8	16	19
carbon	yes	yes	yes
water quantity	yes	yes	yes
water quality	no	only marine	yes
hazard mitigation	no	only coastal	yes
recreation/tourism	yes	yes	yes
ES evaluation	individual	individual	Individual and multiple
scale of operation	local	local and regional	local, regional and global
scenarios	only baseline	only baseline	baseline and land use scenarios
spatial resolution	depends on data	depends on data	1 Km and 1 Ha pixels
potential to influence system development	no	no	Yes
platform	web based	standalone, needs ArcGIS licence	web based
web page	www.ariesonline.org	www.naturalcapitalproject.org/InVEST	www.policysupport.org/costingnature

4.2.1 ARIES (Artificial Intelligence for Ecosystem Services)

ARIES (*alpha* version, www.ariesonline.org) is an ecosystem services valuation tool delivered through a web interface. It is intended to be a global system, but currently only works on several case study sites. It focuses not only on the ecosystem services but also on their beneficiaries, and the links and networks that connects those two. By considering the location of the service source, and where people using that service live, it can calculate the distance and potential barriers to the flow of these services. It aims to produce a comprehensive assessment of the ecosystem services status at a site, considering all the multiple scales that they have influence on. It includes a range of modules to analyse ecosystem services of carbon stock and sequestration, aesthetic viewshed and proximity, flood regulation, fisheries for subsistence, coastal flood regulation, sediment regulation, water supply, and recreation (Villa et al., 2009).

It requires expertise in GIS, some 160-200 hours of work in the development of inputs maps, and, even though it has some global information included, a considerable amount of time and data are required (Waage et al., 2011). Being at *alpha* stage of development, all the information handling and the actual model application is managed by its developers rather than by the user.

4.2.2 InVEST (Integrated Valuation of Environmental Services and Trade-offs)

The suite of models collectively called InVEST (v.2.5.6, www.naturalcapitalproject.org/InVEST) is designed to identify patterns and, given all the necessary data, to provide estimates of value and magnitude of a range of ecosystem services and their trade-offs. It is an open-source stand-alone platform (v.3.x), originally dependant on an ArcGIS environment (up to v.2.5.4). The models deal with ecosystem services separately for terrestrial, freshwater and marine ecosystems. Its modules, in general, are based on functions of productivity of the service and its flow to the users. It includes models for carbon storage and sequestration, coastal erosion and vulnerability, marine aquaculture, aesthetic quality, biodiversity, timber production, water purification, recreation, hydropower production, wave and wind energy production, amongst others. All the parameters for the models are required to be prepared, sometimes from scratch, for a new study site, hence the process may take between 200-300 hours for its application, implying high GIS expertise and basic data availability (Waage et al., 2011). After testing and reviewing some of the case studies, these tools were not responding to the question of how to prioritise current and planned conservation efforts, and even to lesser extent, identifying where future developments would have comparatively less impact on ecosystem services provision, thus this tool was not considered appropriate to the analysis, either.

4.2.3 Co$ting Nature

Costing Nature (CN v.2.45, www.policysupport.org/costingnature) is a sophisticated spatial conservation prioritization tool that allows mapping of a whole range of ecosystem services and their beneficiaries, alongside a series of other conservation-relevant metrics including biodiversity, current pressure and future threat to continued conservation and ecosystem service provision. It accomplishes these results based on the available datasets that are accumulated in the SimTerra database and a set of rule based (i.e. phenomenological) models.

Comparing the three tools (Table 4-1), InVEST and ARIES approach allow for the evaluation of individual ecosystem services, whilst CN handles multiple ecosystem services and multiple threats within the same assessment. InVEST and, to certain extent, ARIES require the user to supply all the necessary data to parameterise the models, and the case studies where they were tested are applied over areas smaller than the study area proposed for this thesis. Comparatively, CN can be applied regionally or locally, through the tile grid, and provides all of the datasets necessary for application anywhere in the terrestrial globe. Requiring a considerable amount of data means high inputs of time and economic resources for model parameterisation, before obtaining any kind of valuable analysis. Co$ting Nature allows rapid and versatile application, and given the focus of this analysis is to run multiple simulations in order to assess the sensitivity of conservation prioritisations according to the inclusion or exclusion of factors (biodiversity, ecosystem services, pressure, threat), it is an appropriate tool for this part of the research. Furthermore, I was able to influence the development of specific functionalities of the model towards including extractive industries as a pressure and threat to ecosystem services.

4.2.4 Modelled Ecosystem Services

Co$ting Nature has a web-based platform of global coverage, divided in a grid system of tiles that area applied individually. Its approach yields a baseline of a multiple-ecosystem service assessment. For this research, a new set of potential future conditions or trajectories under given circumstances, understood as prospective scenarios, were tested and evaluated. The model requires a total of 117 datasets (complete list included Appendix D) to be run properly. These parameters feed the model and ultimately yield a summarised index for each of the following four key ecosystem services: carbon, water provision, hazard mitigation and nature-based tourism.

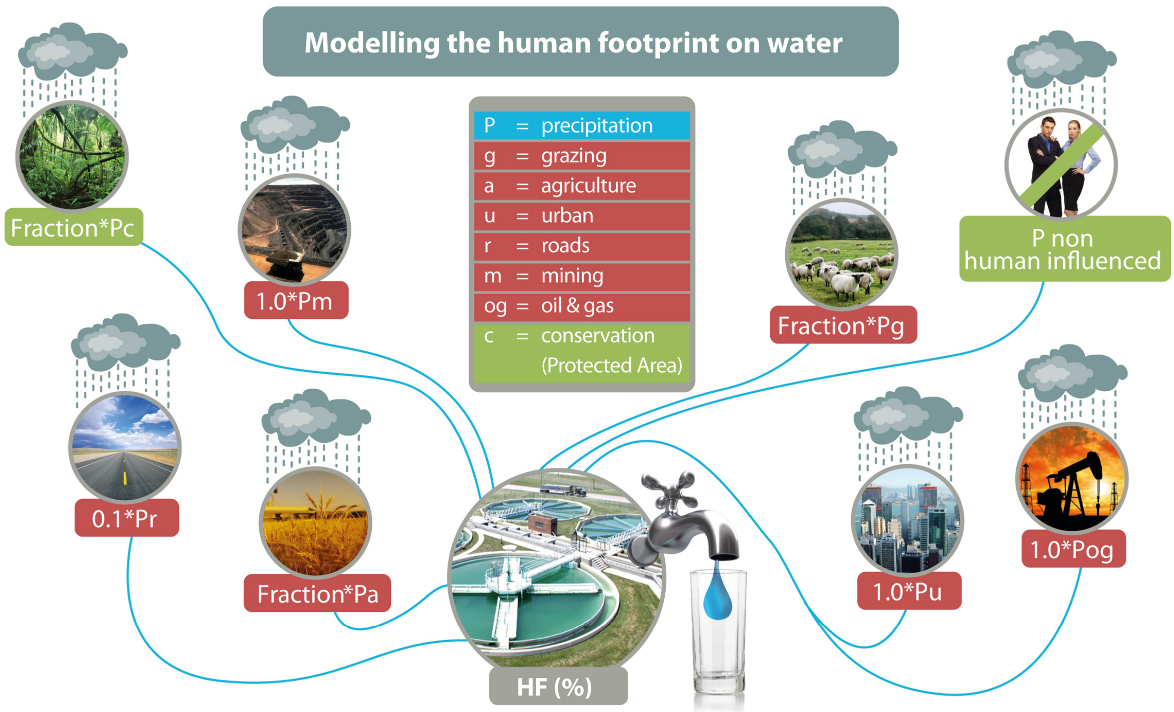
4.2.4.1 CARBON SERVICES

The Carbon value that an ecosystem provides are understood, for the purpose of this study and within the Co$ting Nature model, as the combination of both carbon stock and sequestration. Mulligan (2009) calculated the carbon sequestration from the dry matter productivity (DMP) product of the SPOT Vegetation sensors, thus obtaining global annual values at 1 Km resolution in tonnes of C Km^{-2} yr^{-1}. Carbon stocks are composed of both above- and below-ground carbon. Data for above-ground stocks are derived from Saatchi et al. (2011) and Ruesch and Gibbs (2008), whilst below-ground stocks come from Scharlemann et al. (2009), and they both add up to provide carbon stock at a global scale at 1 Km, expressed in tonnes of C Km^{-2}. Even though it is understood that the sequestration process contributes to the stocks of carbon constantly, the baseline values obtained here can be assumed to be a representative measure of the current situation.

4.2.4.2 WATER SERVICES

Water provision is a service of vital importance with a direct connection to the needs of human populations. The human footprint on water quality (HF) is a compound hydrological metric of water quality that is used by both Co$ting Nature and its sister tool WaterWorld. The HF index is used as a proxy for water quality, since it aggregates human influences on water and cumulates them downstream along the flow network. It is pre-calculated globally for the baseline and it is then modified with land use for scenarios. It counts in the weighed contribution of all mapped human activities that affect water quality: grazing (g), agriculture (a), urban areas (u), roads (r), mining (m), and oil and gas (og). They all pollute depending on the assigned weight, whilst protected areas or zones of conservation (c) contributes by diminishing the human footprint (Figure 4-1).

Essentially, for each pixel in a hydrological drainage network the HF is the sum of flow from upstream that fell as rain on a human influenced land use that may have been susceptible to point (mining, oil and gas, roads) or non-point (croplands, pastures, urban areas) sources of contamination, compared with the total volume of water that fell as rain on all land including that which is not a human land use or is nominally protected and thus is assumed to have no human footprint. For each cell the amount of water that fell as rain on upstream human land uses is combined with the total water available for that cell (from the total water balance information), and the ratio of this "polluting precipitation" to the total water, is calculated and expressed as a percentage (Equation 1 in Figure 4-1). The drainage network for this calculation is derived from HydroSHEDS (Lehner et al., 2008), available in the SimTerra database, along with the layers for land use determining point and non-point human impacts.



Equation 1 $$\text{Human Footprint on Water (HF)} = \frac{\sum P_{\text{polluting}}}{\sum P_{\text{total}}}$$

Figure 4-1 Human Footprint on Water, HF, and its components (adapted from Mulligan, 2009b, design: L. Zurita-Arthos, graphics: D. Zurita)

4.2.4.3 NATURAL HAZARD MITIGATION

Natural hazard mitigation services from an ecosystem are understood, within the Co$ting Nature model, as a function of: *a)* the potential of a hazard to happen, *b)* the exposure of people to it, and *c)* the vulnerability which affects their ability to cope with it. An ecosystem's capacity to mitigate natural hazards are determined by several services, such as: landslides and erosion control, which is assumed to be proportional to the fraction of the area upstream from a cell that is tree covered. Coastal protection, defined by the presence of wetlands and mangrove ecosystems. Flood storage and mitigation, measured by the upstream proportion of wetlands, water bodies, and floodplains; and flow regulation, explained as a function of the tree cover upstream, since it is assumed that, even though trees will consume water via evapotranspiration, they will maintain a base flow during dry seasons in the area by means of enhanced water infiltration compared with agriculturally managed lands (Mulligan, 2012a). All of these services are combined to express the first variable: potential of natural hazard mitigation.

Secondly, the risk of a hazard to occur is accounted for, understood as the result of exposure to hazards (hazard potential combined with measures of human exposure) multiplied by the vulnerability of people to hazards. In order to express these as spatial information, several global indicators are used. To measure the socio-economic exposure to hazards, the model uses GDP density (Gross Domestic Production/unit of area), human population, fraction of croplands and pastures, and infrastructure. The latter is composed, in data, of the presence of roads, urban areas, dams, mines, and oil/gas infrastructures. All these values are normalised in order to obtain a value for exposure for every cell of the global grid. Exposure alone does not show the whole picture, so the hazard potential is also calculated as the average probability of four components: cyclones corrected by the water balance to give an index of erosion/flood hazard as a result of cyclones, coastal inundation for coastal low-lying areas (0-30 masl), landslides based on the upstream slope gradient of a cell, and flooding based on water balance (precipitation minus evapotranspiration). Finally the minimum of exposure and hazard potential indices are taken to represent the exposure to hazard (Mulligan, 2014a).

In a similar manner, vulnerability is thought to be inversely related to the GDP and infrastructure, since the higher GDP and infrastructure development an area, city, or country has, the greater its capacity to cope with a hazard. It is calculated as a normalised index and used to compute the final risk index (Figure 4-2).

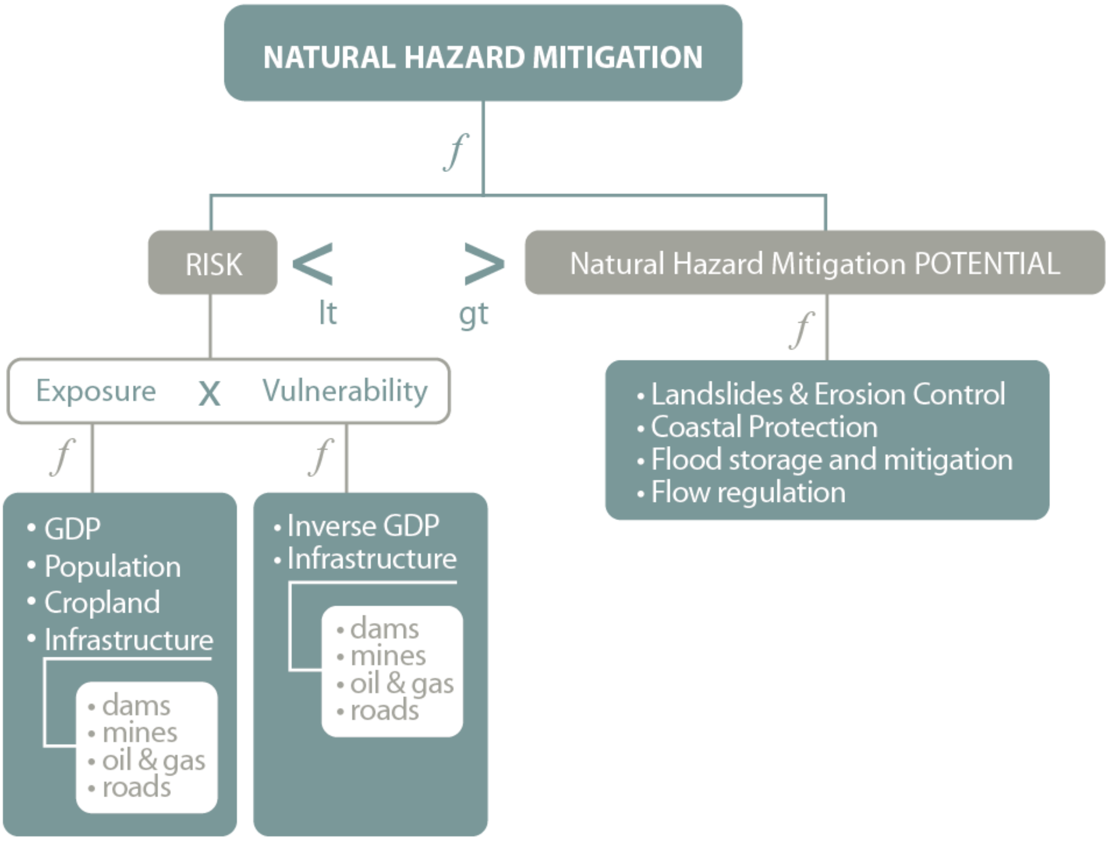


Figure 4-2 Natural Hazard Mitigation Index composition (design: L. Zurita-Arthos, graphics: D. Zurita)

With all the above mentioned variables taken into account, the hazard mitigation service of one cell in the grid is assigned depending on the following rule and train of thought: if the risk is greater than the mitigation potential, then the hazard mitigation service equals the mitigation potential, and there is some risk left "unserved". On the other hand, if risk is less than mitigation potential, the hazard mitigation service for that cell is assigned as the risk, since it is only up to that point that the ecosystem is a service and the rest of the potential remains "unused". This complex relationship of functions and rules is represented in a diagram in Figure 4-2.

4.2.4.4 NATURE-BASED TOURISM

Nature based tourism is understood as a cultural service of ecosystems, since there is no consumption of the natural capital. The benefits can be turned into financial resources for conservation, and the tourist beneficiaries are willing to pay for these services, without major depletion of the source (TEEB, 2013). The Co$ting Nature model uses global data to represent this service as both a potential and realised service. On one hand, the conservation priorities, defined by the simple overlay of the 'BINGOs' conservation prioritisations, are used to represent high value natural places, where nature-based tourism may take place. Then, combined with information on accessibility (Uchida and Nelson, 2009) and population density data (Bright et al., 2008), the model calculates the number of people that would be benefited from these nature services. Hence, the further a 'nature' pixel is from a 'populated' one, the less benefit it would provide. The final index is normalised and corrected for the urban areas, as it is assumed that no nature-based tourism value can be assigned within them. Further details are in the Equation 5 section of Appendix B.

The realised service nature based index is calculated as a global count of georeferenced photographs posted online via the Panoramio service, adapted from the "World touristiness map" algorithm of Heinla (2010). This is, once again, corrected for the urban areas, thus only rural places with high density of photos will have a value for realised nature-based tourism. The global layer was first developed at 0.5 arc degrees of resolution (~50Km at the Equator) using data from 2008 and is resampled by Co$ting Nature to the analysis resolution of 1 Km (Mulligan, 2014)

The prior description of the four main groups of services included in Co$ting Nature has to be further understood, as the model also considers the division between potential and realised services for each of the groups above.

4.2.4.5 Potential vs. Realised Ecosystem Services

An ecosystem service, by definition, can only be considered as such if there are people that are receiving its benefits, although they can be distributed locally (e.g. water provision, hazard mitigation, nature-based tourism) or globally (e.g. carbon, biodiversity). However, the potential of ecosystems to provide these services is also of importance and can be measured through its component. In fact, within Co$ting Nature, every ecosystem service considered has an index of realised and potential services, with the realized services depending on the number and distribution people being benefitting from the service.

Additional documentation of how the model calculates the indices of these ecosystem services are detailed in Appendix E, which are not directly relevant to this research, but can be of interest to further understand how the model obtains its results.

4.3 Methods

To begin with, it was necessary to set the baseline scenario, which is an ecosystem services assessment based on mean climate data (mean of the period 1950-2000) and land cover data for the period of 2000. For the purpose of this chapter's research, version 2.45 of Co$ting Nature was used. Once the baseline was set, it was possible to develop potential scenarios according to different strategies of conservation. The model was run at the regional scale of the Western Amazon, which implies a sextuple matrix of tiles. Then, the proposed prioritisation scenarios were only run within one tile, focusing on relevant oil and gas concessions and other mining extractive operations. In the following sections I describe the basic assumptions and caveats of the model and its various metrics, and how these were used to answer the questions about how and where conservation should be prioritised.

4.3.1 BASELINE SCENARIO FOR THE WESTERN AMAZON

In order to maintain coherence with the previous standalone study on oil impacts and ecosystem services, this next study was set within the same geographical boundaries: latitude 10°N to 20°S, and 80°W to 60°W of longitude. Co$ting Nature (v.2.45) was set to run within individual tiles of 10 degrees (at 1-square-km spatial resolution, Figure 4-3). Thus, a total of six different tiled analyses were necessary to cover the whole area of study. The spatial resolution of the analysis was set to 1-square-km in common with the analysis of Chapter 3.

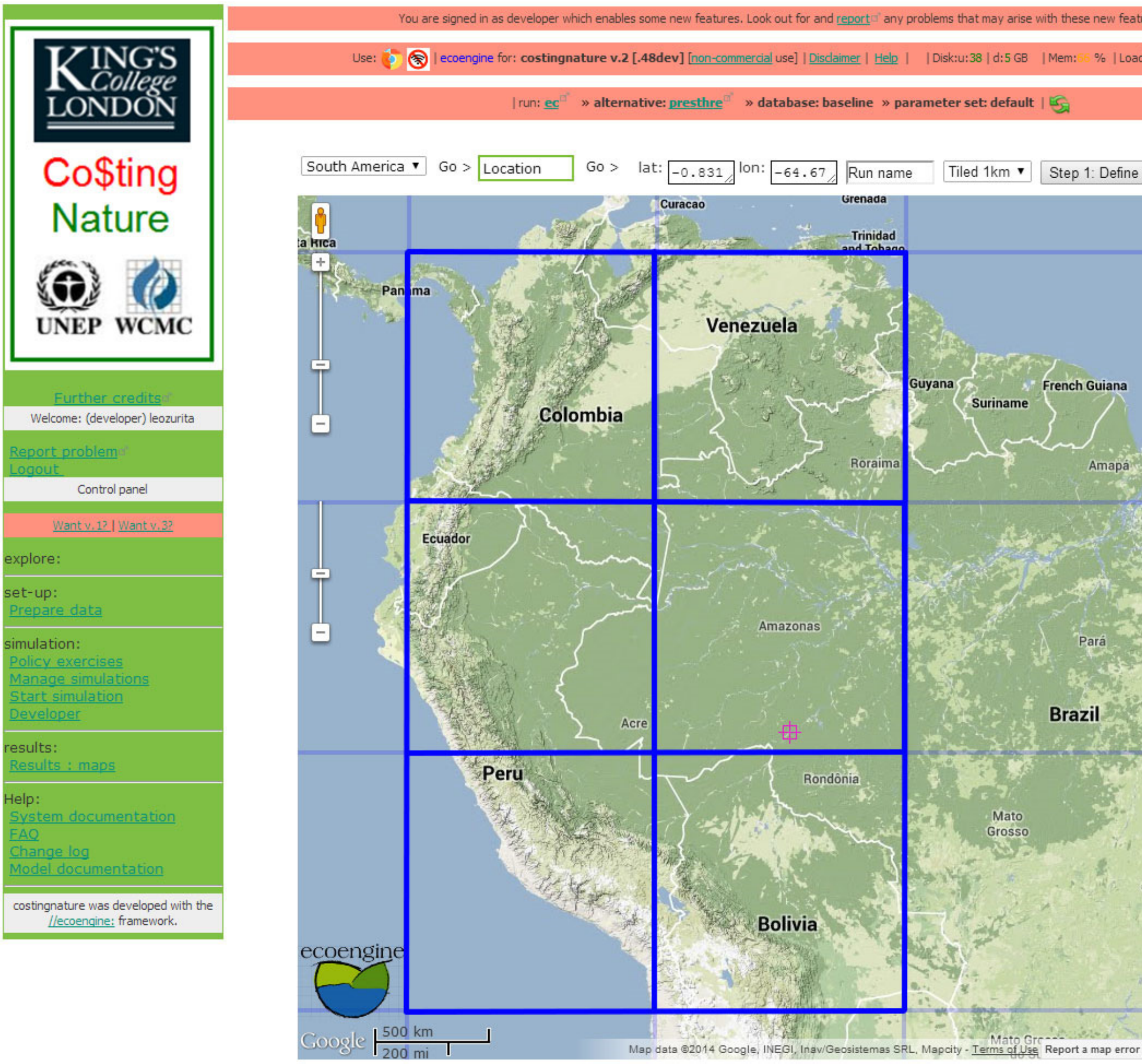


Figure 4-3 Costing Nature web interface showing the tile arrangement at 1 Km resolution and highlighting the sextuple matrix that covers the Western Amazon

Amongst the 117 parameters, input as maps, that the Co$ting Nature model needs, there are a variety of metrics for ecosystem services, biodiversity, pressure and threat which differ immensely in their units of measurement. In order to make these metrics work and be part of the model calculations, they are first normalised and scaled from 0 to 1 globally, where 0 represents the global minimum for the variable and 1 represents the global maximum value. I prepared the data and ran a baseline simulation for all six tiles. For each tile, the resulting information was visualised to confirm their correct calculation and downloaded in a .map format, which is a PCRaster format. The resulting tiles derived from CN, were then merged accordingly to generate full Western Amazon datasets. That is, with all of the outputs of the model placed in a common geodatabase, a short PCRaster script was written and run in order to merge the six tiles for each variable into one basemap. This was achieved by using the function `resample` of PCRaster, for every one of the model outputs. The model derives a total of 34 different outputs from the baseline run.

For the purpose of this study, two important additional processes where tailored to fit within the model and are of major consideration for the results and analysis. First, the Western Amazon basin boundary (as defined by HydroSHEDS) was set as an analysis mask, looking to avoid any bias on the results from the distinctively different ecosystems in the Andes and Pacific Coast of South America. However, the basin, and hence the study area, does contain some of the highlands of the Eastern Andes, including the headwaters of the Amazon river, in the Mismi snow-covered mountain (above 5,500 masl), of this ~6,500 Km-long river (Lee, 2014). Secondly, a more detailed and up to date (as of December 2013) coverage of the oil concessions in the Western Amazon was gathered for the three countries (Ecuador, Peru and Colombia) in order to improve the SimTerra dataset. This coverage allows for a better definition of the boundaries of the oil blocks.

4.3.2 Ecosystem Services Current Status and Expected Future in the Oil Extractive Areas

A focused analysis with Co$ting Nature was setup for the area where the combination of oil activities and high ecosystem provision has been identified within the Western Amazon (Zurita and Mulligan, 2013, Finer et al. 2013). The areas of Northeastern Ecuador (Lago Agrio, Sacha, Coca and Auca oil fields), Southeastern Ecuador (Yasuni National Park, and Kichwa, Shuar and Shiwiar indigenous territories) and Northeastern Peru (Loreto region) are known for their richness of natural resources. Oil and gas activities are either under exploitation, or under exploration in these areas. Several separate studies have recognised the high numbers of species in the region of all groups of biodiversity, and a few have touched upon the mapping of ecosystem services (Bass et al., 2010; Finer et al. 2010; Neeff et al., 2005). This whole region is currently under severe pressure due to the oil activities of the past, present and likely the near future. Consequently a detailed spatial prioritisation effort could be of immense value for policy making and enforcement by local stakeholders. For this study, a tile of 10 x 10 degree between 70-80 degrees west of longitude and 0-10 degrees south of latitude (Figure 4-4)

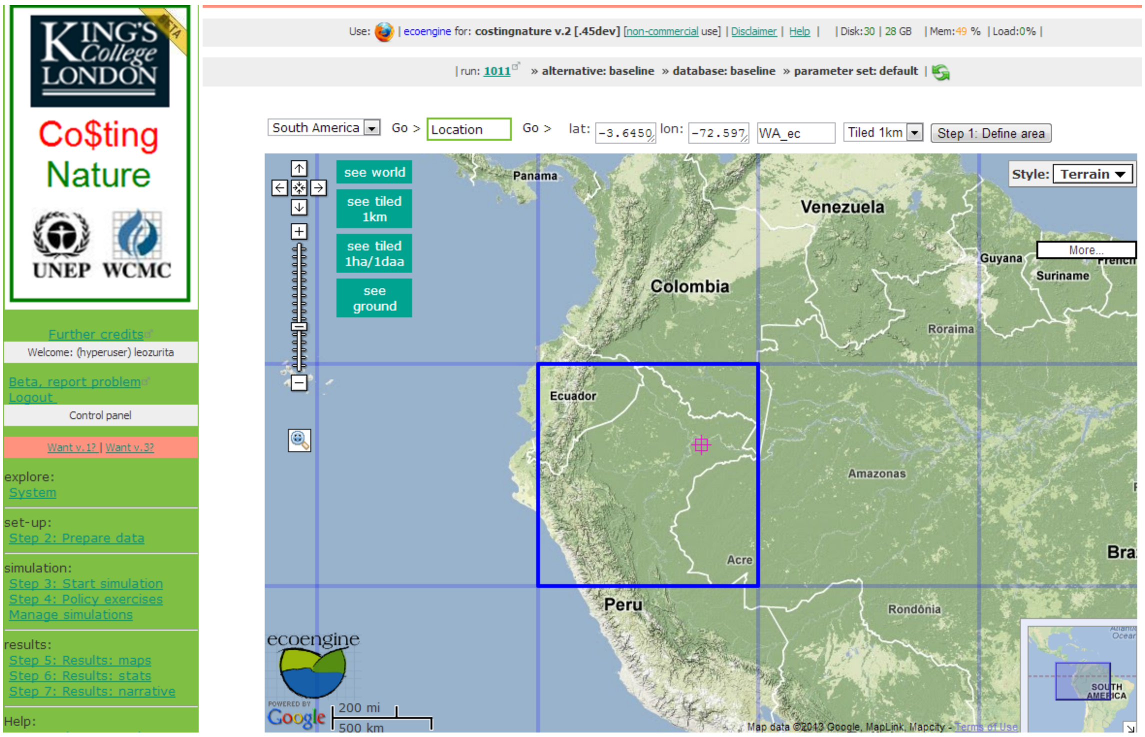


Figure 4-4 Co$ting Nature web interface showing the tile arrangement at 1 Km resolution, covering the focus area in Ecuador and Peru

Table 4-2 List of ES relevant outputs derived from Co$ting Nature.

parameter (s)	Index	units
Carbon (C)	Relative **carbon** value index	0-1 globally
Natural Hazard Mitigation (HM)	Relative **potential** hazard mitigation ecosystem services	0-1 globally
Nature-Based Tourism (T)	Relative **potential** nature-based tourism index	0-1 globally
Water Provision (W)	Relative **potential** water provisioning services index	0-1 globally
Natural Hazard Mitigation (HM)	Relative **realised** hazard mitigation ecosystem services	0-1 globally
Nature-Based Tourism (T)	Relative **realised** nature-based tourism services index	0-1 globally
Water Provision (W)	Relative **realised** water provisioning services index	0-1 globally
Biodiversity (B)	Relative **biodiversity** index of **threatened** species (mammals, amphibians, reptiles, birds)	0-1 globally
Conservation (CO)	Relative conservation priority index	0-1 globally
Current Pressure (PR)	Relative pressure index	0-1 globally
Future Threat (TH)	Relative threat index	0-1 globally
Human Footprint on Water (HF)	Human footprint on water quality (percentage of potential contamination)	%
C, HM, T, W	Relative total **potential** services index	0-1 globally
C, HM, T, W	Relative total **realised** bundled services index	0-1 globally
B, CO, PR, TH	Relative total nature conservation priority index	0-1 globally
C, HM, T, W, B, CO, PR, TH	Relative total ES and nature conservation priority index (**potential** services)	0-1 globally
C, HM, T, W, B, CO, PR, TH	Relative total ES and nature conservation priority index (**realised** services)	0-1 globally
C, HM, T, W, B, CO, PR	Relative total development priority index (**potential** services)	0-1 globally
C, HM, T, W, B, CO, PR	Relative total development priority index (**realised** services)	0-1 globally

Bundle indices comprise several parameters

A summary of the relevant outputs to evaluate conservation strategies was derived and presented in Table 4-2. The first column shows the parameter or mix of parameters that were used to calculate the indices in the second column. The third column shows the units and ranges for these indices. The first group of rows in the table correspond to the base data for every individual ecosystem service as described in detail above. These indices are of great importance by themselves to evaluate and establish a baseline scenario. However, further analysis is possible when comparing all the services as a bundle, hence the bottom group of indices highlighted in green bring together the previous ones according to simple average calculations. Furthermore, ecosystem services combined with nature conservation priorities represent a more comprehensive assessment for conservation than other single metrics. Conversely, identifying areas under current pressure and low ecosystem services provision, would result on development priority metrics where future extractive operations could potentially take place. Due to the importance and, in some cases, complexity of the indices calculated, individual sections follow below.

4.3.2.1 *Threatened Biodiversity index*

When looking at nature, it is very common to first think about biodiversity, and even though it is not considered a service by itself, it does have an undeniable intrinsic value (Oksanen 1997), and is considered as part of the supporting services of an ecosystem upon which the remaining services rely (Ghilarov, 2000). Co$ting Nature focuses in threatened species richness and threatened endemic species derived from the IUCN red-lists for amphibians, reptiles, mammals and birds. It is assumed to be a spatial proxy to represent the patterns of biodiversity distribution. Particularly in this case, as extractive industries are a potential threat to biodiversity conservation, highlighting taxa that is categorised as threatened helps to bring to light the most relevant regions where high numbers of vertebrate species should be designated for conservation. Other taxa, equally important, such as plants, and invertebrates are not included in this index only due to the lack of readily available datasets at global extent. However, using vertebrate threatened biodiversity to direct conservation will help towards diminishing biodiversity loss at all levels (Butt et al., 2013). The biodiversity index combines the mentioned taxa, originally expresses in number of species, in one normalised measure combining both richness and endemism.

4.3.2.2 Conservation Priority

As explained in the Study Area section (Chapter 2), the conservation prioritisations led by the BINGOs is an important measure to consider when looking at prioritisation. These delphics are considered in Co$ting Nature within one inclusive index called Conservation Priority, which overlays the global databases of areas defined as Important Bird and Biodiversity Areas (Birdlife), Biodiversity Hotspot (CI), Global 200 ecoregions (WWF), Last of the Wild (WCS), Alliance for Zero Extinction Site (IUCN), and calculates a normalised index to express them, by which areas covered by all the conservation efforts reach a maximum value of 1, and areas with no priority for conservation get a value of 0. This is done, as all data in Co$ting Nature, at a global scale.

4.3.2.3 Pressure index

The Costing Nature model does not only include the considerations on ecosystem services and biodiversity mapping and measurement, but it also looks at the risks of losing them. Hence, the current pressure that these ecosystems are experimenting is a reasonable variable to include and consider within an analysis. In fact, this index measures, with global datasets, the combined influence of population, fire frequency, grazing and agricultural intensity, dam density (number of dams upstream from a point or cell in the grid) and infrastructural density (point or site location of dams, oil and gas infrastructure, mining sites, roads and urban areas). This index, as all the others, is normalised and measured globally within a scale of 0 to 1.

4.3.2.4 Threat index

The future threat that an ecosystem may be facing due to planned infrastructure is included as a combined index of the foreseen changes in pressure. The threats of land use change, climate change and infrastructural change are included here. Land use change is more likely to occur in proximity to already changed areas, as it has been observed by research on roads and deforestation rates around them (Barber et al., 2014). The model uses MODIS VCF imagery

(Sexton et al., 2013) and Terra-I data (Reymondin et al., 2012) to examine proximity to current deforestation frontiers. Climate threats are derived and scaled from the mean of 17 GCMs (General Circulation Models) projection for the scenario A2a from the AR4 report of the IPCC (International Panel on Climate Change), for temperature and precipitation changes forecast for 2050. For infrastructural change it is assumed that the remote facilities of mining sites, oil and gas locations are of importance in determining future threat as are planned roads. These three threats are weighed equally and represented as a normalised index of threat.

4.3.2.5 TOTAL POTENTIAL BUNDLED SERVICES INDEX

The total bundle of potential ecosystem services is the normalised sum of all potential ecosystem services considered within the model. It includes potential water provision, potential hazard mitigation, potential nature-based tourism, and carbon services (Figure 4-5). The latter, being a regulating service, is the same carbon value for both potential and realised services, as explained above in sections 4.2.4.1 and 4.2.4.5 of this chapter.

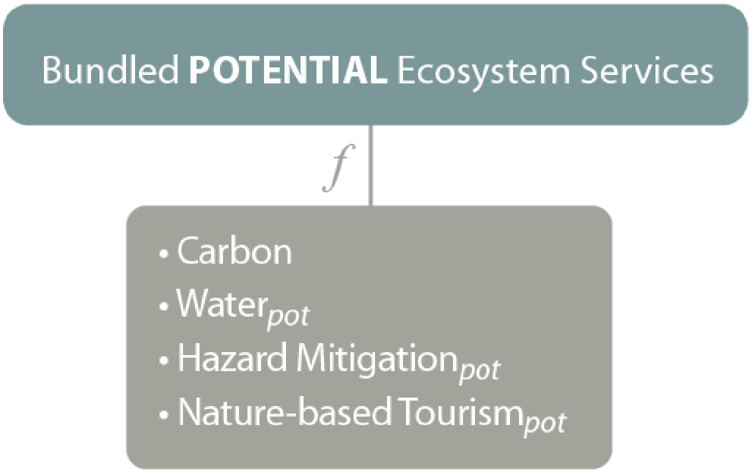


Figure 4-5 Total bundled potential ecosystem services and its components (design: L. Zurita-Arthos, graphics: D. Zurita)

4.3.2.6 TOTAL REALISED BUNDLED SERVICES INDEX

The total services that are currently benefiting people are calculated, within Co$ting Nature, as the normalised sum of the realised services for water provision, hazard mitigation, nature-based tourism, and carbon (Figure 4-6). As with the previous metric, this is a bundle of services, and it is assumed here that it is better to display all these ecosystem services as one, particularly for prioritisation purposes, where a comprehensive index (i.e. all ecosystems included) is a much more useful one.

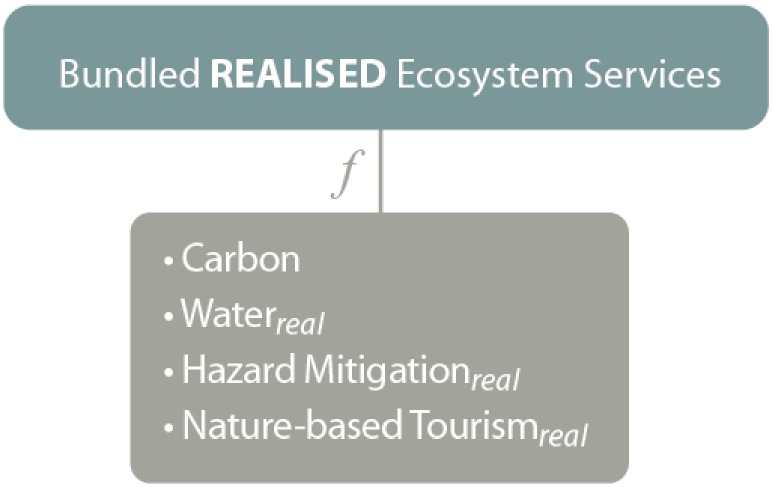


Figure 4-6 Total bundle of realised ecosystem services and its components (design: L. Zurita-Arthos, graphics: D. Zurita)

4.3.2.7 Total Nature Conservation Priority

This index is the combination of natural variables and the risk of losing them are included in the model. The normalised combination of biodiversity value, conservation priority, current pressure, and future threat form this index (Figure 4-7). This intermediate index allows us to show where the conservation efforts can be directed if nature is the only main concern, leaving ecosystem services aside.

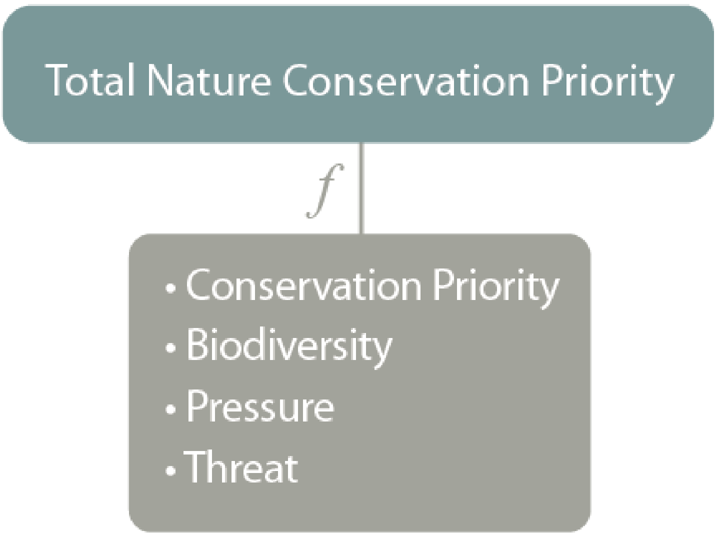


Figure 4-7 Total nature conservation priority and its components (design: L. Zurita-Arthos, graphics: D. Zurita)

4.3.2.8 TOTAL CONSERVATION PRIORITY INDEX

This index aims to include all the relevant variables for conservation prioritisation, since it is formed of all the nature conservation priority variables together with the ecosystem services bundle (Figure 4-8). That is considering equally valuable, hence giving equal weight to, biodiversity, conservation delphics, pressure, threat, carbon, water provision, nature-based tourism, and hazard mitigation services. Indeed it shows the whole picture to consider within an area when looking at the options to prioritise conservation, particularly thinking of the most efficient way to spend a rather limited, and progressively decreasing, source of funding for these efforts.

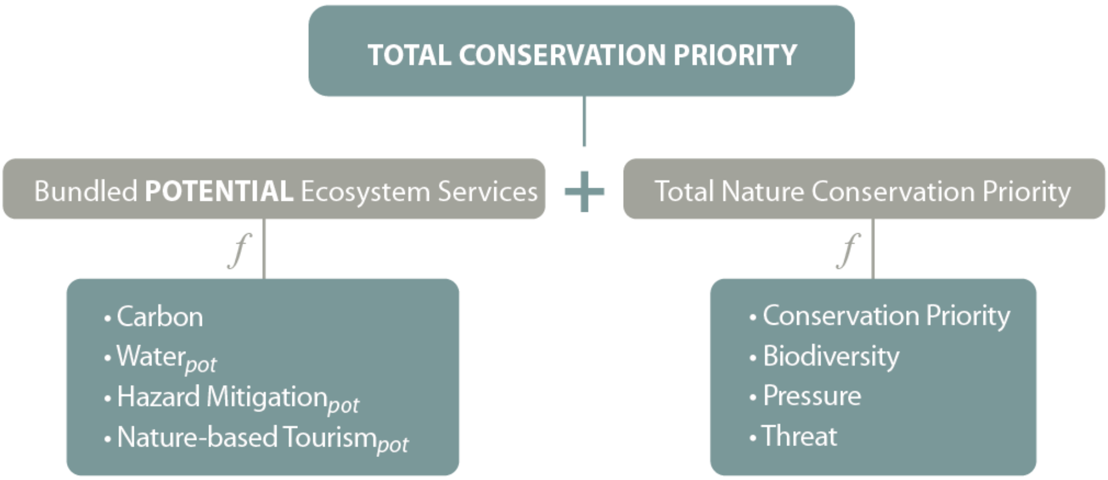


Figure 4-8 Total conservation priority index and all its components (design: L. Zurita-Arthos, graphics: D. Zurita)

4.3.2.9 RELATIVE TOTAL DEVELOPMENT PRIORITY INDEX FOR POTENTIAL SERVICES

This index aims to show areas with relative low conservation value, which are already under pressure. That is, the combination of current pressure with biodiversity value, conservation priority, as well as water, carbon, hazard mitigation and nature-based tourism potential services. In other words, the higher the value in this index, the lesser the impact to be expected from future development in this areas. Since population density is part of the pressure dataset, areas with high development index would have few people dependent – or likely to be dependent in future – upon the provision of ecosystem services. The caveats and limitations to consider are that only available datasets are included for biodiversity and current protected areas coverage. Hence, areas potentially recommended for development may include relevant taxa of biodiversity, or indigenous territories that were not included in the inputs that yield the index.

4.3.2.10 Relative Total Development Priority Index for Realised Services

Similarly, the relative total development priority index for realised services combines the current pressure, with nature variables (biodiversity and conservation) and the bundled realised ecosystem services (Figure 4-9). The idea behind this is the assumption that areas that are currently under pressure are already developed or semi-developed, and their conservation value has already been impaired, hence future development should be better be carried out in these areas, rather than in other areas with higher value for conservation, and consequently lower value of this development index. These areas also have few people dependent upon their provision of ecosystem services.

Figure 4-9 Total development priority index for realised ecosystem services and its components (design: L. Zurita-Arthos, graphics: D. Zurita)

4.3.3 Preparing Scenarios for Conservation Prioritisation

The purpose of this analysis is to understand the conservation priority baseline for this region using CN's default combination of indices in which pressure, threat, ecosystem services and conservation priority are equally weighted in the final metrics. Then, I analysed the impact of changing valuation (weighting) of ecosystem services and of conservation priority metrics. A series of scenarios were designed and then implemented within the Co$ting Nature tool. Basically, I changed the weighting assigned to the different components of the overall conservation priority. In each case the effectiveness and coverage of the current conservation efforts relative to the defined conservation prioritisation was assessed.

Three distinct scenarios are proposed, aiming to test different prioritisation approaches by changing the weightings assigned to the components of the model, and ultimately inform a more objective and comprehensive approach that can be of help in the processes of decision and policy making as well as testing the outcomes of different prioritisation assumptions. Within Co$ting Nature, a built-in tool was developed based on the objectives for these *policy exercises*. The scenarios were prepared, run, and then compared with the baseline. For the baseline run, all conservation priorities are weighted equally, or evenly prioritised. Then, within each of the three scenarios that were set up, the same components are included, but with changes in the weights assigned to each component according to the priority that the scenario aims to highlight.

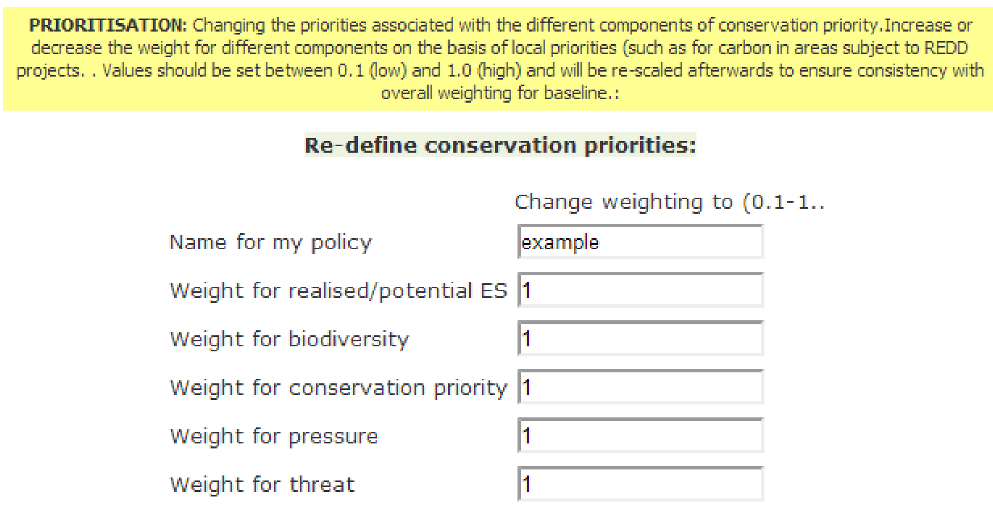


Figure 4-10 Prioritisation settings to model potential scenarios within Co$ting Nature

In the first scenario, I maximised the weights given to the parameters of conservation priority and biodiversity; on the second, I turned the focus mainly to Ecosystem Services (both realised and potential), and finally, in the third scenario, a maximum priority is given to areas under current pressure and future threat. These represent three wholly different scenarios or potential policy options: *a)* proactive biocentric (CONS), *b)* proactive anthropocentric (ES), and *c)* reactive (pressure and threat based, PRTH), which are setup through the option of policy exercises in CN, assigning the weights according to the approach as established in Table 4-3.

Table 4-3 Baseline scenario (BSL) and proposed weightings assigned to the policy options for prioritisation of Conservation/Bio-centric (CONS), Ecosystem Services/Proactive Anthropogenic (ES), and Pressure and Threat/Reactive (PRTH).

Component \ Policy option →	BSL	CONS	ES	PRTH
realised/potential ES	1.0	0.1	1.0	0.1
biodiversity	1.0	1.0	0.1	0.1
conservation priority	1.0	1.0	0.1	0.1
pressure	1.0	0.1	0.1	1.0
threat	1.0	0.1	0.1	1.0

maximum weight

minimum weight

4.3.4 Conservation Scenario

Conservation efforts in any area are predominantly dependent on both funding and willingness of local populations and governments (Fearnside, 2003). Since they both are commonly scarce, prioritisation actions towards maximising the effects of these efforts becomes essential. In the first policy option, priority is given to the conservation of biodiversity where the BINGOs (big international Non-Governmental Organisations) have identified the need to protect the life and habitats of the species over these areas, which have been aggregated in the above-mentioned Conservation Priority index. In the same way, a maximum weight is assigned to Biodiversity, which accumulates data of mammals, birds, reptiles and amphibians, as it was defined above in section 4.3.2.1. The other three main components of the model are left to the minimum weight possible, and with the five values set, the model was run (Table 4-3). The prioritisation here is given to the nature components, aiming to highlight the importance of these conservation efforts and compare these results with the current system of protected areas in order to draw potential prioritisation conclusions for future conservation.

4.3.5 Ecosystem Services scenario

This policy option emphasises the importance of Ecosystem Services above the other components of the model. As shown in Table 4-3, it assigns minimum weight to biodiversity and conservation priority, as well as to pressure and to threat, and thus the weight for the analysis to ecosystem services is maximised. This is aimed to emphasise the importance of ecosystem services, both realised and potential, and ultimately to show a more comprehensive approach to conservation, where the benefits that ecosystems are providing now, and the potential services that they can provide in the future, should be included and targeted for future areas of conservation, and avoid, if not all, major infrastructural development that can cause severe impacts.

4.3.6 Pressure and Threat scenario

In this last scenario, maximum priority is given to emphasise current pressure values, as well as to future threat to the ecosystems, which is a reactive type of scenario. Hence, minimum weight is assigned to ecosystem services, conservation priority and conservation (Table 4-3). This approach aims to highlight where the ecosystems are currently suffering impacts, or will likely be in the near future. By doing this, one can try and pinpoint the source of these impacts, for instance by masking the results with the oil concessions, and from there advice on what measures can be taken to minimise these impacts in the future. This approach will ultimately show the areas with low current pressure and high threats foreseen in the future so they can be targeted for conservation.

4.3.7 Scenarios Analysis

The results of the baseline scenario and the potential strategies for conservation were analysed by selecting the top 17% of land (according to Aichi Target 11) that should be prioritised. The regions that are consistently within the top 17% were considered the topmost priorities for conservation and summarised as no-go zones for extractive or other activities than may harm the integrity of these ecosystems. Ultimately, this is a tangible result that informs a decision making process and it is proposed as a policy of 'no-go extractives'.

4.4 Results

4.4.1 Baseline Results and Analysis

The most relevant parameters to evaluate conservation strategies were identified above in Table 4-2, because they respond to questions about mapping ecosystem services, biodiversity and conservation priorities in the Western Amazon, thus their results are presented and analysed as a baseline scenario that established the current status of the issues. Though the indices are scaled 0 to 1 globally in Co$ting Nature, I re-scaled them from 0-1 regionally at the Western Amazon for this study. This re-scaling allows for a regional understanding of the patterns and priorities displayed by the metrics, and also is a more appropriate way to compare them with each other, independent of their units, since the indices are dimensionless. Table 4-4 shows the mean of the results for the Western Amazon, which are further explained and analysed in the following sections.

Table 4-4 Mean and standard deviation values for the indices for the Western Amazon region (normalised regionally, 0-1). The last five highlighted indices are bundles of several parameters.

Variable Western Amazon = 4,2 million Km2	**units**	**MEAN**	**STD**
Relative **potential carbon** value index	0-1 regionally	**0.4958**	0.1408
Relative **potential hazard mitigation** ecosystem services	0-1 regionally	0.5246	0.197
Relative **potential nature-based tourism** index	0-1 regionally	0.0002	0.003
Relative **potential water provisioning** services index	0-1 regionally	**0.8923**	0.2221
Relative **realised hazard mitigation** ecosystem services	0-1 regionally	0.0146	0.0335
Relative **realised nature-based tourism** services index	0-1 regionally	**0.0124**	0.0493
Relative **realised water provisioning** services index	0-1 regionally	**0.0536**	0.0317
Relative threatened **biodiversity** index of red-list species (mammals, amphibians, reptiles, birds)	0-1 regionally	0.7405	0.1557
Relative **conservation priority** index	0-1 regionally	0.3742	0.1841
Relative **pressure** index	0-1 regionally	0.0628	0.1266
Relative **threat** index	0-1 regionally	0.7006	0.0456
Human footprint on **water quality** (% contamination)	% (percentage)	10.7692	22.2083
Relative **total potential** services index	0-1 regionally	0.7136	0.1771
Relative **total realised** bundled services index	0-1 regionally	0.4971	0.133
Relative total nature conservation priority index	0-1 regionally	0.6582	0.0724
Relative total ES and nature conservation priority index **(potential** services)	0-1 regionally	0.7363	0.1191
Relative total ES and nature conservation priority index **(realised** services)	0-1 regionally	0.6805	0.0881
Relative total development priority index **(potential** services)	0-1 regionally	0.6212	0.0881
Relative total development priority index **(realised** services)	0-1 regionally	0.8557	0.0309

4.4.2 Realised and Potential Ecosystem Services in the Western Amazon

As discussed above, CN makes a clear distinction between potential ecosystem services and realized ecosystem services (section 4.2.4.5). In general, all the individual potential services within the Western Amazon vary gradually across the lowlands, particularly when reaching the Andes slopes in the western upper parts of the basin. In fact, the boundary of the basin define a clear barrier of change in the variable behaviour, which is related to the change in type of ecosystems, and urban population.

Potential services

The carbon value map (Figure 4-11*a*) shows highest carbon values in the lower lands of the Peruvian Amazon, and these maxima are due to the associated peat soils with high organic carbon content of up to 50,000 t C/km^2 (Scharlemann et al., 2009). The upper quartile of the data here is located in the western limits of the basin where both carbon sequestration and stocks (above and below ground) are high. The two processes are linked together since carbon sequestration is an active process which contributes permanently to the carbon stocks (Mulligan, 2014a). The amount of this contribution depends on the time lapse considered, though carbon sequestration is normally expressed in metric tonnes of carbon per year.

The potential of water provision for the Western Amazon is comparatively the highest valued potential service. The mean value across the 4.2 million Km^2 is at 0.89±0.22 (scale 0-1 regionally), is explained by the vast majority of the water balance (precipitation minus evapotranspiration) not being polluted by human activities. In fact, this service is maximised in most of the forested area of the Western Amazon, whilst, the minimum values are point or local sources of contamination in urban areas across the region, croplands in Rondonia, Brazil, and interestingly for this study, the oil and gas region in Northeastern Ecuador.

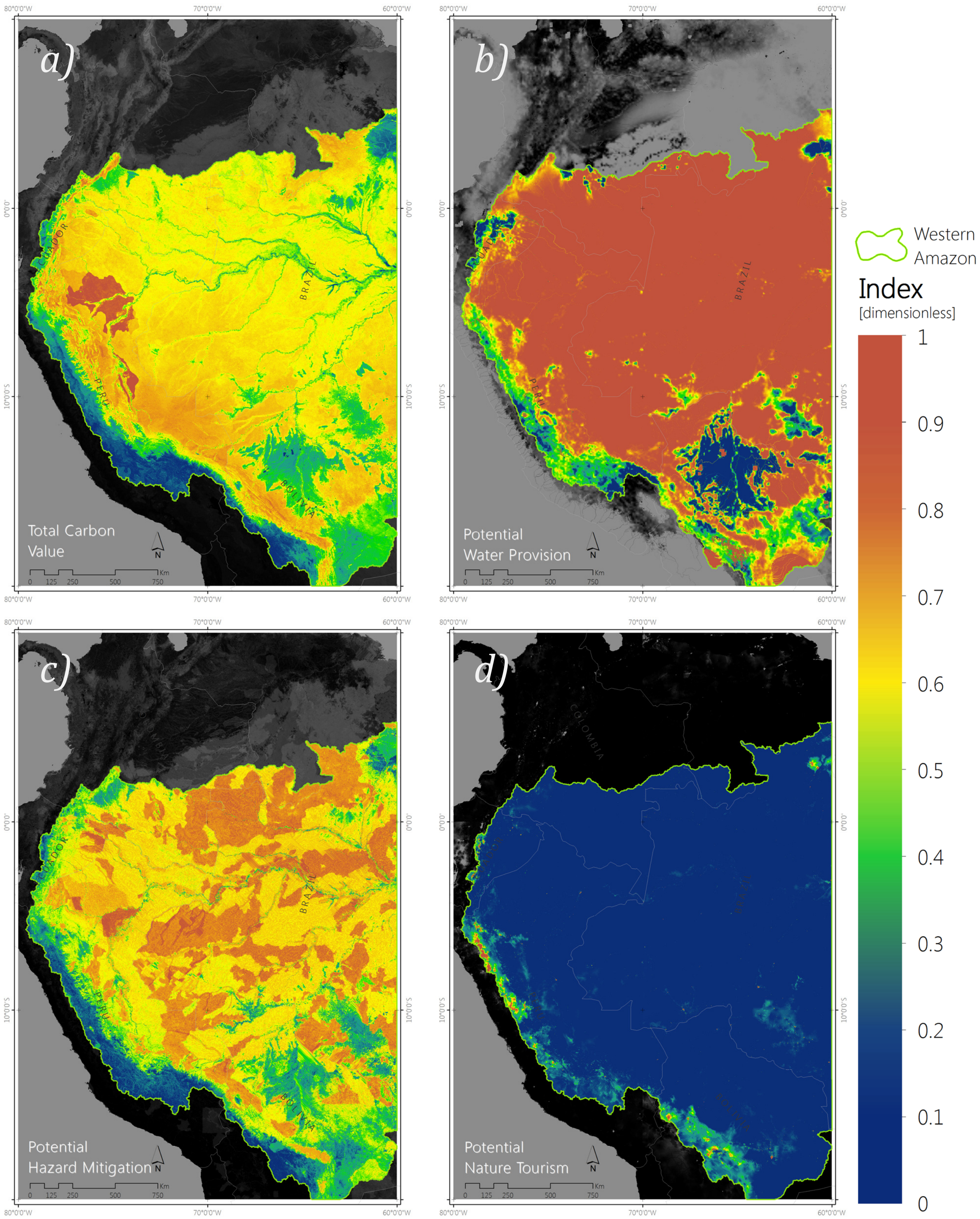


Figure 4-11 Potential Ecosystem Services calculated for *a)* carbon, *b)* water provision *c)* hazard mitigation, and *d)* nature-based tourism (normalised and scaled 0–1 regionally) for the Western Amazon

These local values are close to zero on water potential provision, and these impacts are carried downstream causing decrease all the way across the Peruvian Amazon and reaching the tri-national boundary point in Leticia, Colombia, where the Amazon River flows through Peru, Colombia and goes into Brazil (Figure 4-11*b*).

The hazard mitigation *potential* services map (Figure 4-11*c*) shows a different pattern, which is dominated by the mitigation services of water bodies and vast floodplain areas that are protected (as part of a protected area from the WDPA 2012). It also has a high correlation with tree cover, which is counted positively in the index, as it provides protection against erosion and landslides, on one hand, and also helps on drought mitigation. Lower values indicate relatively low service provision, especially in the southern part of the basin, where despite being natural and well-maintained ecosystems, such as the shrub forest and inundated forest in the Bolivian Amazon, the tree cover fraction is close to zero. Since it is a naturally flooded area, the value for hazard mitigation is expected to be low. Nevertheless, most of the basin reports high potential for natural hazard mitigation with an average of 0.52 ± 0.19 (scaled 0-1 regionally), which adds up to the importance of the basin as a whole.

Potential recreational services are, in average, low since nature-based tourism requires both of natural areas and infrastructure that makes it accessible. Most of the Amazon is still not nearby highly populated areas (the CN algorithm uses distance to the nearest town of 50,000 persons or more as a threshold to calculate accessibility, from Uchida and Nelson 2009); and it also has a limited road network, which lowers the potential service provision as figure 4-11*d* shows. However, the lack of accessibility can potentially work as a barrier to avoid large scale deforestation and land use change. The recreational service shows a few localised areas in the Andes of Peru and Bolivia with high potential provision, mainly in the vicinities of large towns and cities. These areas have simultaneously high conservation value (based on the conservation delphics), scenic view potential (based on slope), and low human footprint on water (based on the percentage of the water balance that may be polluted).

Alternatively, when summarised by protected areas, there are high potential values over small protected areas in the Andes, such as the Cutervo National Park in Peru, or areas of high mountains, such as the Huascaran National Park, where the White Ridge shows one of the highest potential recreational services, which is also highly realised, as discussed in a later section.

Realised Services

The realised services for the region depend on where people are located and using the services. In the case of carbon services, being a global regulating service from which we all benefit in a relatively equal manner, both potential and realised carbon services are assumed to be the same (i.e. all potential carbon services are realised), and the Carbon Value index represents them (Figure 4-12*a*).

Realised water provision is highest in the small sub-basins that provide water to urban areas, particularly in the Andean region, where the population is relatively high and water flowing downstream, with low human footprint, is being used (Figure 4-12*b*). The frequency distribution of approximately 90% of the data is below the 0.05 bar, which shows how the location of a service is very important when its beneficiaries simply cannot have access to it. Furthermore, the maintenance of the current realised services is crucial for populations depending upon them, particularly in areas such as the *altiplanos* in Bolivia, where the water sources are scarce and their demand is on the raise.

Hazard mitigation services are only realised in the areas close to where people are living and benefitting from the mitigation of potential hazards. There are only a few big urban areas in the region, so low values are expected to be present in the majority of the region. Looking at the frequency distribution more than 90% of the data has values below 0.1, which makes the few actual hazard mitigation services very localised. (Figure 4-12*c*).

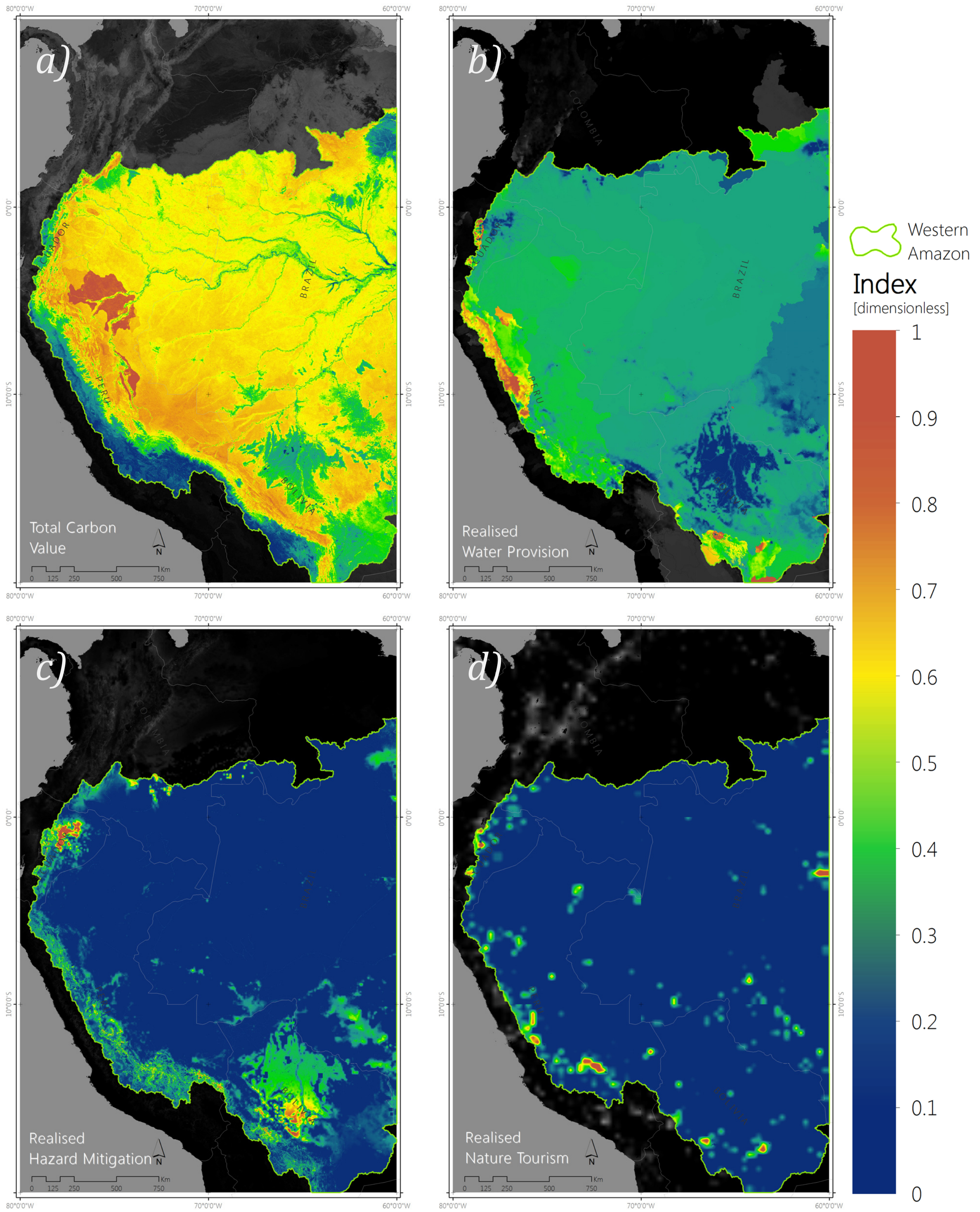


Figure 4-12 Realised Ecosystem Services calculated for *a)* carbon, *b)* water provision *c)* hazard mitigation, and *d)* nature-based tourism (normalised and scaled 0–1 regionally) for the Western Amazon

Realised recreational services reach peak values in several point locations in the Western Amazon, from high mountain areas in the Cotopaxi and Tungurahua volcanoes in Ecuador, to the Sacred Valley and Inca trail in the Cuzco to Machu Pichu, and in the east of the study area, the forested area upstream from Manaus at the "Meeting of the Waters" where the Solimoes River joins the Negro River to form the Amazonas from that point until it reaches the Atlantic (Figure 4-12*d*).

All these areas showed localised high index value due to their elevated nature value for actual tourism, as defined by the number up geo-tagged photographs uploaded to Panoramio services by different users per unit area (Mulligan, 2013b). Despite these few peaks, most of the nature-based tourism services are low in the Western Amazon, with a mean of 0.01± 0.05 (scale 0-1 regionally).

When comparing potential and realised ecosystem services alongside, the differences come to light. As expected, carbon services remain the same, and areas as the Pacaya Samiria region thrive for their high carbon values (Figures 13*a* and 13*b*). In terms of water provision, the realised average is very low (0.05) compared to the potential mean (0.89). Regions of oil and gas extraction in Ecuador provide low water services in general (Figure 13*c*). Areas in the Andes as the White Ridge provide high actual water services for the population downstream (Figure 13*d*). When comparing hazard mitigation services, on average there are about 50 times more potential hazard mitigation services that are left unused in the region as a whole. Areas as the Yasuni and Cuyabeno in Ecuador, or the Javari Valley in Brazil, are well prepared to mitigate natural hazards (Figure 13*e*). Moreover, these areas are also home to isolated human groups (Phillips, 2011; Rival *in press*), which brings up their cultural value and uniqueness, although this is not considered within this study. However, mitigation services are not transferable, so they are highly realised locally upstream, particularly in areas where infrastructure is found, such as the oil and gas extraction regions of Ecuador (Figure 13*f*).

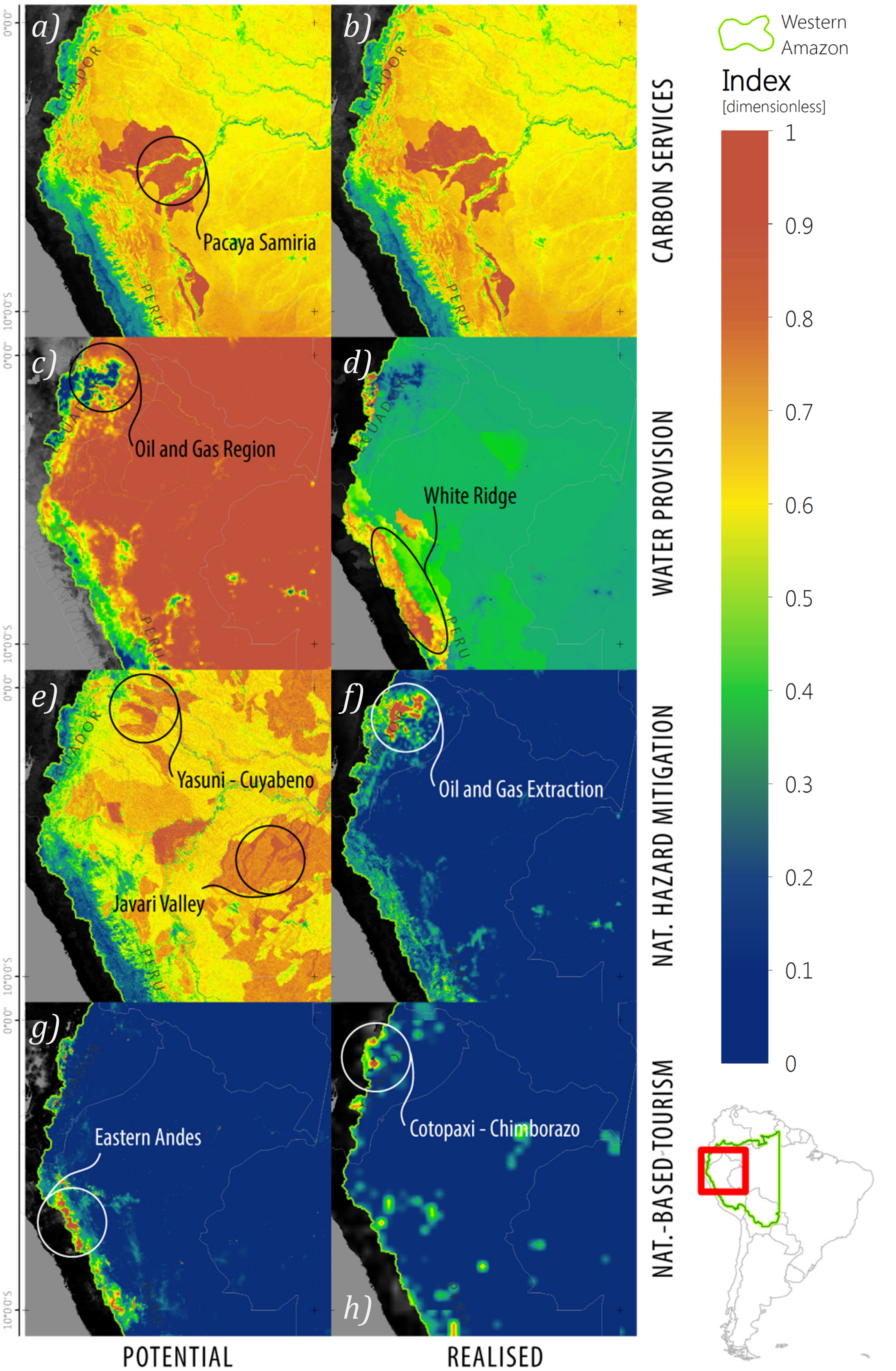


Figure 4-13 Potential and realised ecosystem services comparison for *a-b)* carbon, *c-d)* water provision, *e-f)* hazard mitigation, and *g-h)* nature-based tourism for a focus area in the Western Amazon

The eastern Andes in Peru and, to a minor extent, in Ecuador are potential places for high nature-based tourism, due to their natural scenic view as hill sides, combined with their accessibility through the existing road network (Figure 13*g*). Comparatively, the already mentioned mountains of Cotopaxi and Chimborazo in Ecuador are the current high spots for realised nature-based tourism (Figure 13*h*). These differences can help discerning new potential places that provide services, and consequently should be conserve.

4.4.3 NATURE CONSERVATION PRIORITY

As it was established, the nature conservation priority is a bundled index. These bundles take into account that an ecosystem may provide various services at once and they are only separated for the purposes of measurement and valuation. Hence, deconstructing this index, the biodiversity map (Figure 4-14*a*) highlights the overwhelming importance of conserving the entire Amazon for its threatened biodiversity. Particularly the lower slopes and evergreen rainforests of the Ecuadorian, Peruvian and Brazilian Amazon, with comparatively lower values observed for the upper areas of the Andes within the Western Amazon. In general, the biodiversity index averages at 0.74±0.16, which is comparatively high amongst the rest of indices, and it contributes greatly to the combined nature conservation priority index.

Looking at the overlapping layers of the conservation priority index (Figure 4-14*b*), most of the Western Amazon is included in at least one of the big international NGO's priorities. In fact, a total of 60% of the area shows values above 0.3, with an average value of 0.37±0.18 (scaled from 0-1 regionally). Maximum values are localised in small regions in the lower forests of the Peruvian Amazon, by the Manu National Park at Madre de Dios, and crossing towards the forests in the region of Rio Branco in Brazil.

The map of relative current pressure (Figure 4-14*c*) shows several recognised tendencies in the Western Amazon. Recent land use change can be seen across the whole region in point sites where deforestation is occurring, and along rivers in the upper parts of the basin where hundreds of dams are located, as well as busier road networks, connecting urban areas.

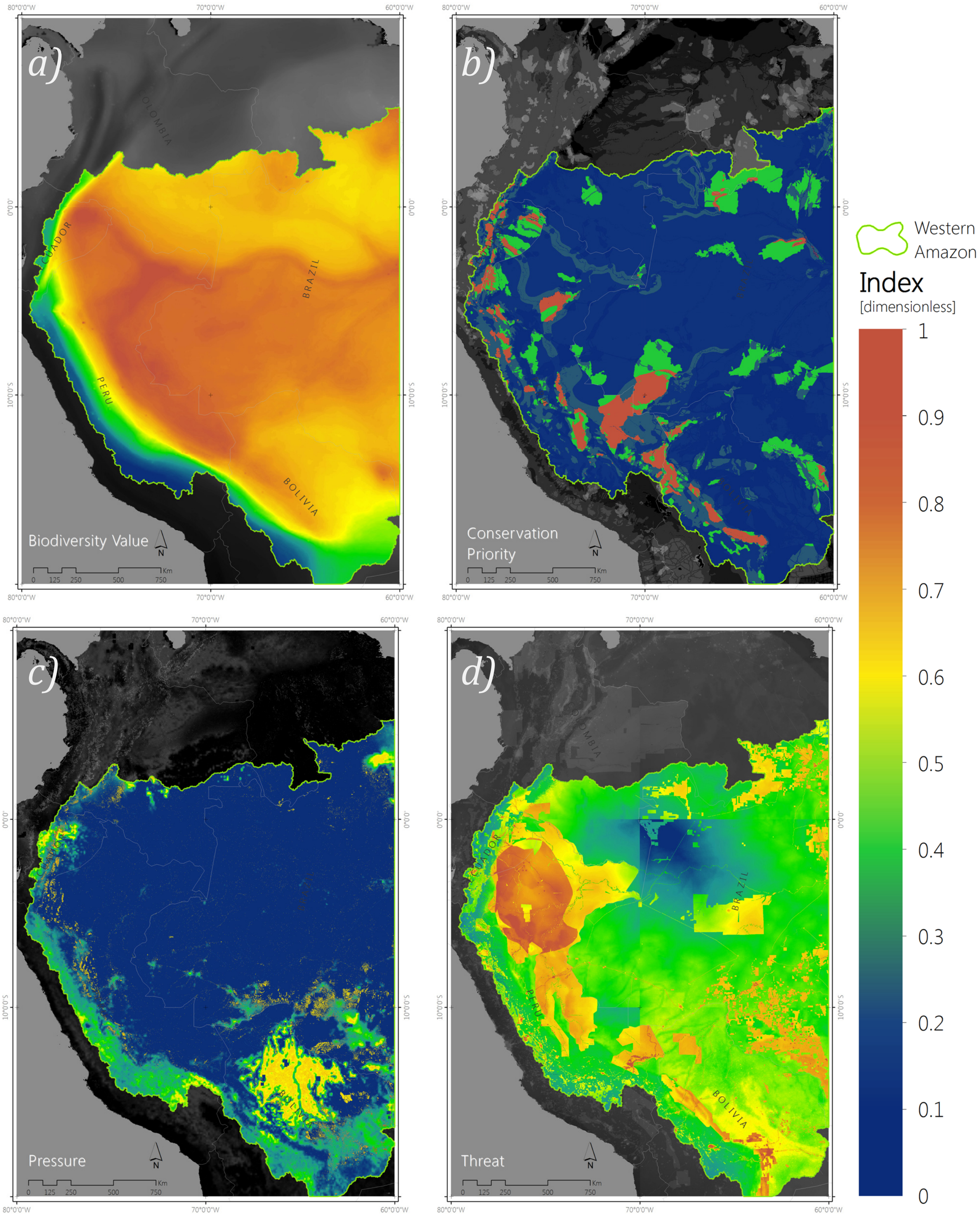


Figure 4-14 Nature Conservation Priority index composition showing *a)* Biodiversity Value, *b)* Conservation Priority, *c)* Current Pressure, and *d)* Future Threat indices for the Western Amazon

Furthermore, highest point values are found in the highly oil developed areas of North eastern Ecuador, and the dispersed effects of grazing and agriculture can also be identified in sites where these human activities take place. Despite all of these, the mean relative value is low at the regional level reaching 0.06±0.13 (scaled from 0-1).

The map of future threat (Figure 4-14*d*) shows where the development is heading in the near and far future. Above ground the road plans can be identified going across the Brazilian Amazon in the centre and south of the basin, connecting the currently remote areas and changing the accessibility to urban areas and the natural resources in the region. Thus the large areas with high values correspond to the oil concessions, which currently cover a small part of the Colombian and Brazilian Amazon, and the vast majority of the Ecuadorian and Peruvian Amazon. The potential reserves of coal in the Peruvian Amazon are also visible through this index. Mining concessions are recognised by the smaller blocks in the south-eastern region of the Western Amazon. The maps shows an effect of the tiling from CN in the central area. This is likely related to the tile based calculation of distance to deforestation fronts, and it is a recognised limitation of the model. Overall, the region has a mean value for threat of 0.70±0.05 (scaled from 0-1 regionally), with a minimum value over the whole region of 0.56, which should be of major consideration when prioritising conservation efforts.

4.4.4 Bundled Ecosystem Services and Combined Indices

Potential

The bundled potential ecosystem services shows contributions from the water provision across the region, which means there is particularly good quality water flowing down from protected areas. Carbon services respond to high values of carbon stock in the soils and carbon sequestration as biomass (Figure 4-15*a*). In this context, the entire Amazon region shows a high potential of provision of services, which should be taken into account for future plans of development that would cross through these areas, such as the mentioned IIRSA (IIRSA, 2013).

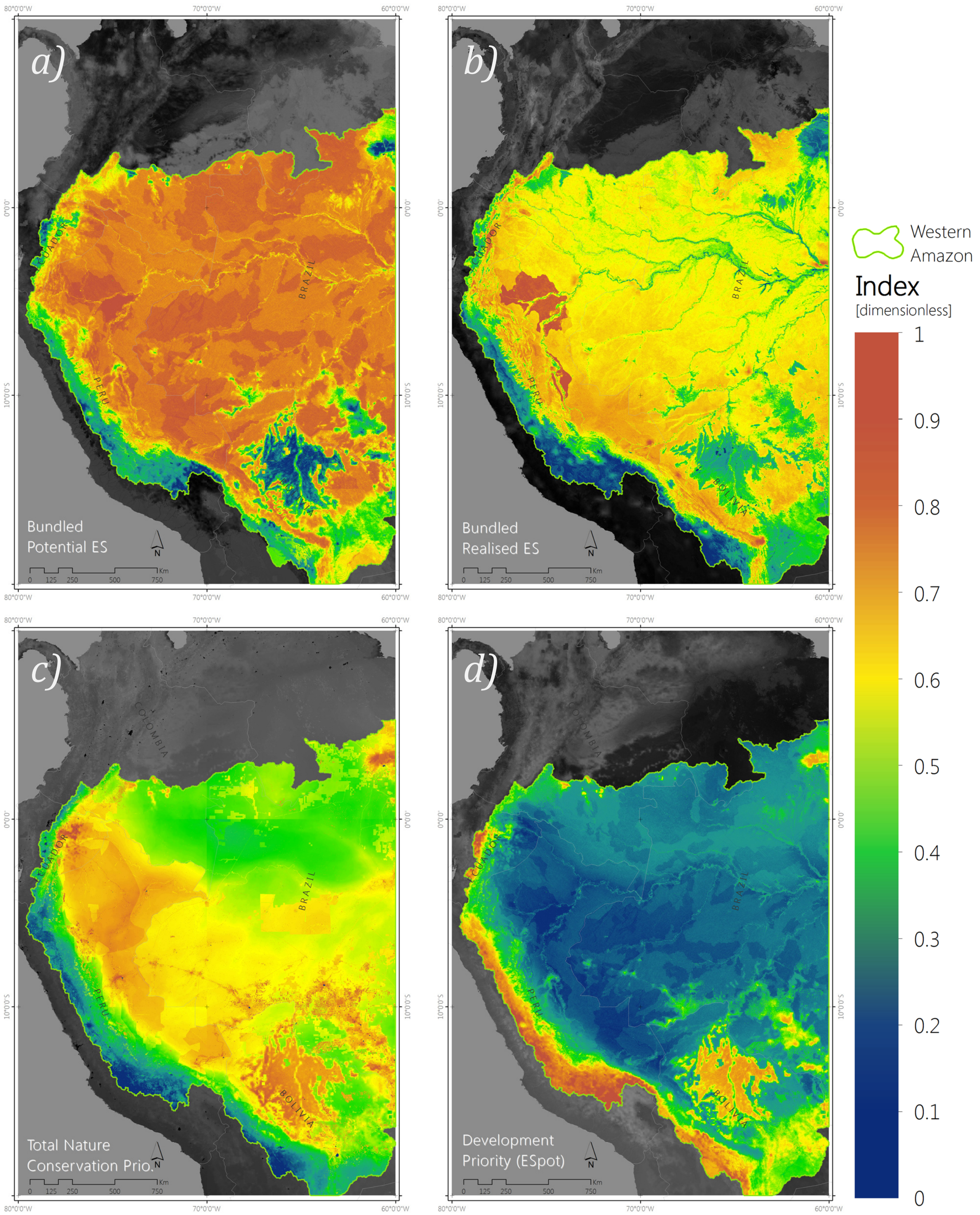


Figure 4-15. Bundled indices for *a)* Potential Ecosystem Services, *b)* Realised Ecosystem Services, *c)* Total Nature Conservation Priority, and *d)* Development Priority for Potential Ecosystem Services, normalised and scaled regionally (0–1) for the Western Amazon

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For the realised services, the maximum values of the index are directly related to the high carbon value, as it can be seen in NorthEastern Peru (Figure 4-15*b*). High values are also observed within the boundaries of several protected areas. This is due to their water provisioning services, as it can be seen in the Ecuadorian Andes, as well as the water and mitigation services in the Negro River just upstream from Manaus in the Eastern limits of the area of study. A similar situation is found in the Bolivian Amazon where the National Park Amboró, west of the city of Santa Cruz, provides high benefits of carbon and realised nature-based tourism.

The Nature Conservation Priority Index map (Figure 4-15*c*) displays maximum values where high current pressure and future threat coincide with high values of biodiversity and conservation priority. Hence, oil concessions and coal reserves are clearly marked especially where they overlap. Threatened biodiversity is high over the whole western region. None of the ecosystem services are taken into account in this measurement, hence it is a pure measurement of 'nature'.

In figure 4-15*d*, it is possible to observe the distribution of areas where a constructive trade-off can be identified for future development. Regions where the current pressure is already high, and ecosystem services provision is considered to be low, can be targeted for development with minor loss of ecosystem services. One caveat to consider is that not all relevant data for biodiversity and protected areas are included in the index calculation, hence these results should expressed with this limitation. Nevertheless, the total development priority map shows the least harmful areas where future development should take place. In general, these areas are already under pressure, which means closer to where people already live, and are found in the Andes slopes in the western edge of the study area. Oppositely, the big carbon reservoirs of the Peruvian Amazon (shown in blue shades in Figure 4-15*d*) should be regarded as a high conservation priority.

4.4.5 TOTAL CONSERVATION PRIORITY

The final baseline index analysed merges all relevant variables for conservation within this study (i.e. C, W, HM, T, B, CO, PR, and TH). The total conservation priority for the Western Amazon places it as an important source of both global (i.e. carbon) and local (i.e. water, recreational, hazard mitigation) ecosystem services. Only a small proportion of pixels in the map (the Andes and some non-forested areas) show ecosystem services provision comparatively lower (Figure 4-16). However, some of those services may be of high importance at a local scale, since they were normalised at the regional level from their original global indexing. The highest ranked areas coincide with recognised zones of high provision of ecosystem services and of grand importance for conservation. Overall, conservationists' claims, experts' opinions (Naughton-Trevess et al., 2005; Wendland et al., 2010; Bhagabati et al., 2014), and now this modelling approach agree about the importance of the Amazon as a whole, so some priorities must be set, and they should include the top relevant areas which encompass all the previous considerations. Looking in detail at the patterns in Figure 4-17, the oil and gas regions in Ecuador have already depleted their potential to provide ecosystem services and protect biodiversity in comparison with the rest of the Ecuadorian Amazon. Similarly, in Brazil the highly deforested State of Rondonia, and to the west the city of Rio Branco are not providing the potential services their natural ecosystem once did. On the other hand, the Beni savannah in Bolivia is not a high provider of all considered ecosystem services, although their natural cover of grasslands has not been affected. Thus, understanding the context of the natural vegetation cover is important to interpret this results properly.

The prioritisation process is further analysed within the 17% of the area (~700,000 Km^2) with the highest value for 'conservation'. This threshold was identified as a pertinent as it was agreed in Aichi Target 11 for 2020, by the CBD 10th Conference of the Parties and all its signatories (IISD, 2010).

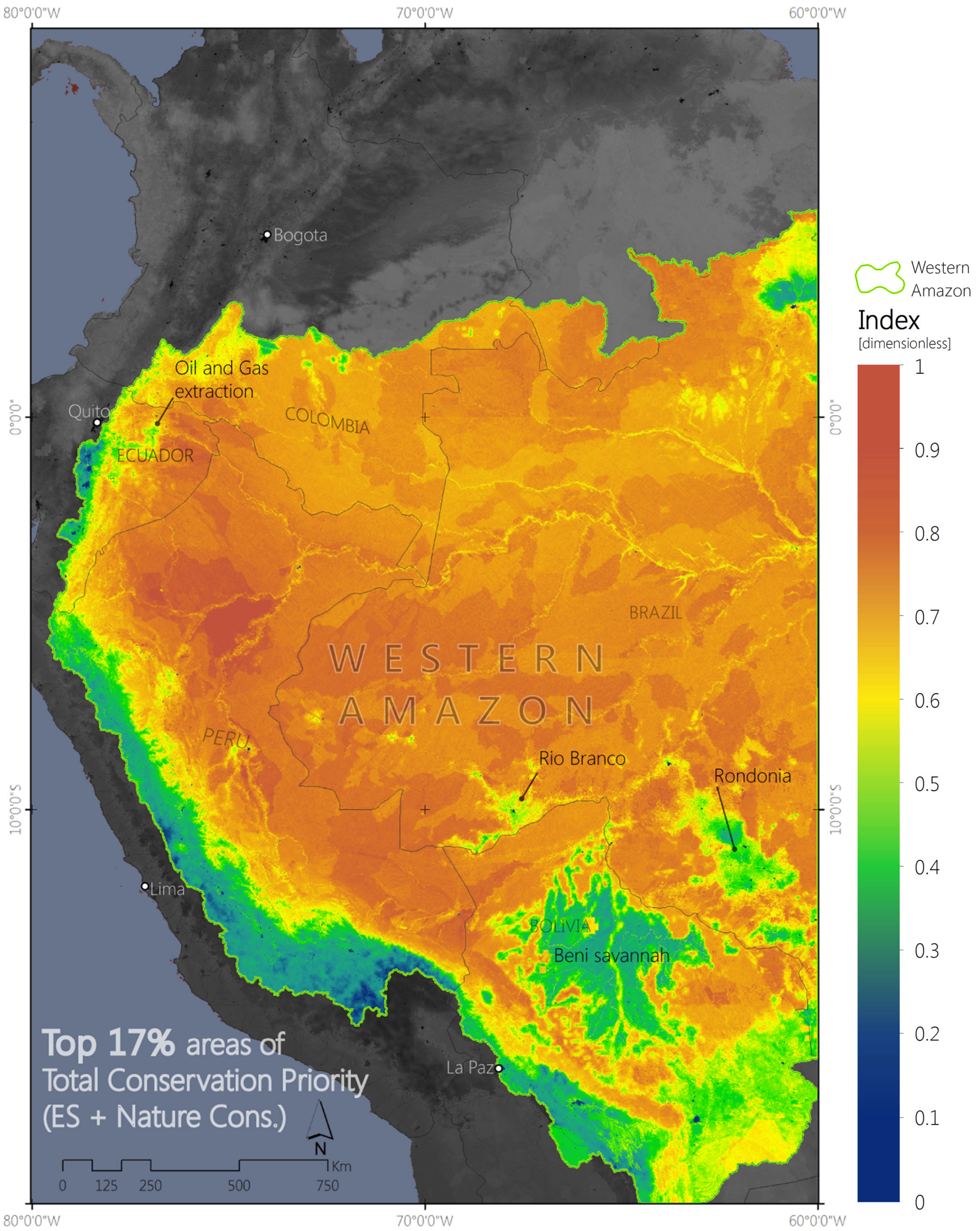

Figure 4-16 Total Conservation Priority Index (normalised regionally from 0–1) for the Western Amazon

New patterns are observed in Figure 4-17 which is masked by the top 17% of areas with highest value of total conservation priority, placed the highest priority to the areas of the Peruvian Amazon. This area of the Western Amazon is particularly important due to the high combination of ecosystem services provision and elevated numbers of biodiversity under threat. The Pacaya–Samiria National Reserve is located in the region of highest conservation priority. It protects around 20,000 Km^2 of forest and it includes the riversides of the Marañon River, which later meets the Ucayali to form the Amazonas River in Peru (Soria, 2004). This particularly high values are attributed to the reserves of carbon in the forest and the soil underground, as well as the water provision services that are abundant in the region, and the high numbers of threatened biodiversity that inhabits the area. However, overhunting in this region has already caused local extinction of some large mammals (Bodmer et al., 1997). The pressure coming from the neighbouring city of Iquitos and more importantly the potential threat of oil and gas concessions in the region bring implications of national concern for Peru and international importance for the region. The socio-political ramifications of these results can be of help in the decision-making process at the local level and even the development of a regional policy that protects these high-valued areas for conservation. For instance, the Andean Community (CAN) brings together representatives of Colombia, Ecuador, Peru and Bolivia, and it recently formed the Council of Ministries of Environment and Sustainable Development, whose functions include promoting and recommending cooperation mechanisms that produce a regional environmental policy that preserves the environment (CAN, 2014).

The region of the Yasuni National Park together with the Cuyabeno Fauna Reserve, in Ecuador, are also included amongst the top 17% with high carbon, water and hazard mitigation services provision. The Brazilian Amazon also has some very important areas to prioritise, such as the indigenous territories of Javari Valley and Biá River, as well as the Reserves for Kanamari and Deni groups. All the mentioned regions were found of importance previous research focused on biodiversity and human pressure over the region (Bass et al., 2010, RAISG, 2012a).

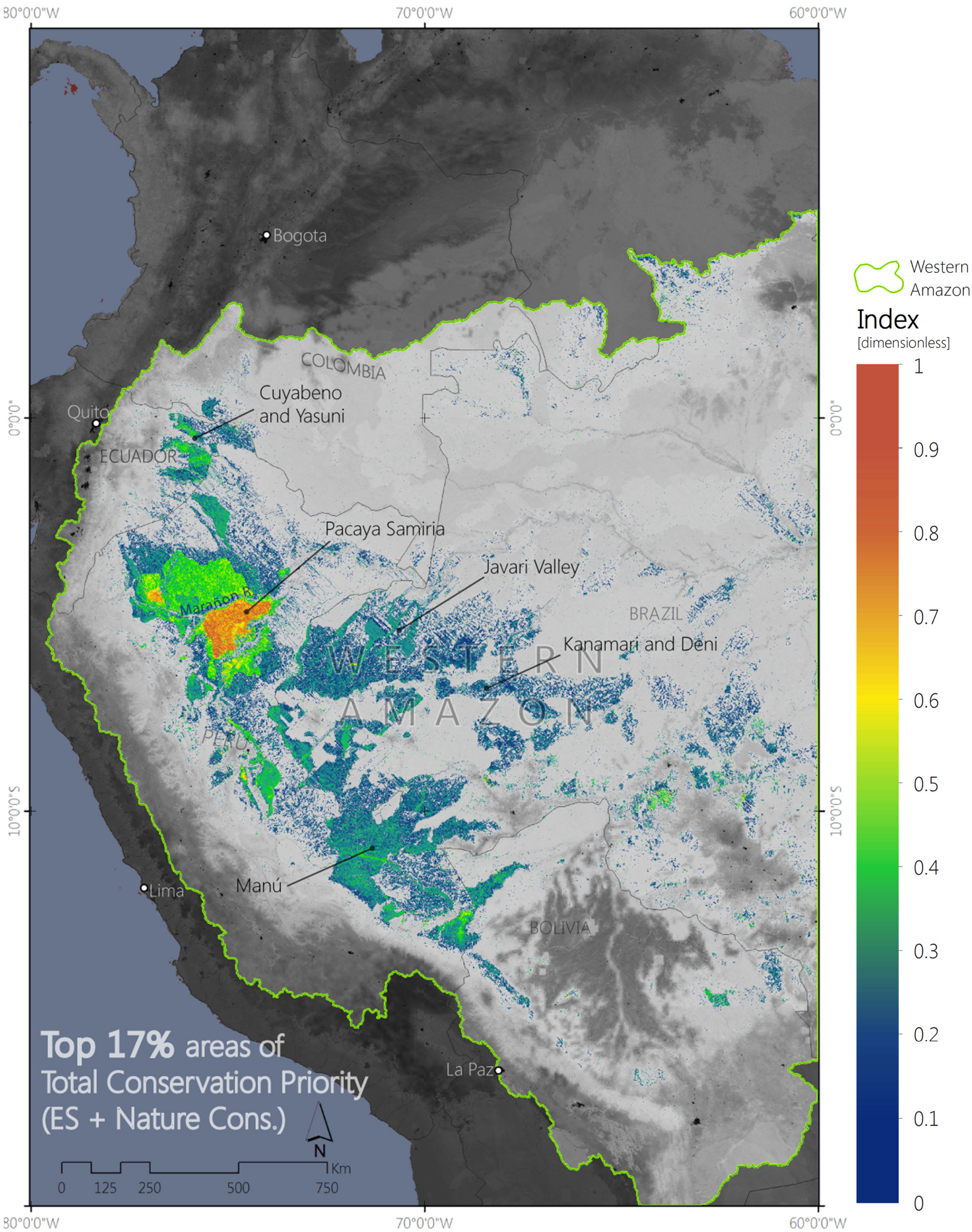

Figure 4-17 Top 17% of the area of Total Conservation Priority, equivalent to 700,000 Km²

Lastly, this top 17% account for 700,000 Km^2 of the Western Amazon, in which, despite being an area with low population density, approximately 90 million people live (according to LandScan data, Bright et al., 2008), and consequently depend on these ecosystem services.

4.5 Conservation Priorities in the Oil Extractive Areas

Establishing and analysing the baseline scenario helped to understand and already suggest potential priority areas based on the analysis of ecosystem services provision and threatened biodiversity weighted equally. As it was described in the methods (section 4.3.3), this study goes beyond the baseline scenario, and evaluates three policy options that prioritise different components. Regions heavily used by oil and extractive industries were used to focalise this part of the study, and compared the results.

These oil and gas extractive areas account for 45% of the Western Amazon section of this tile in Ecuador and Peru. This is explained by to the actual size of oil concessions (also known as oil blocks) and it coincides with previous studies that highlighted the extensive nature of the oil and gas industry (Finer et al., 2008). Even though the infrastructure and extractive activities occupy only a small portion of the land, the on-site impacts on ecosystem services are transported through the water flow network, and this is one of the unique contributions of the model and this study. Furthermore, the modelled impacts of these localised activities can be seen in the surrounding areas due to the interpolation and buffering techniques applied to the data.

The Ecosystem Services (ES) scenario weighted them as a priority, and as a result it showed highest values for three out of five of the bundle indices analysed (Figure 4-18) Comparatively with the others, the ES scenario is the most comprehensive strategy for conservation. Nevertheless, the Conservation (CONS) policy option is the most effective to highlight areas for biodiversity conservation, with decent conservation of ecosystem services as well.

Looking in more detail at the indices, the Total Conservation Priority in the ES scenario is in average two times higher than the rest (mean=0.75 for ES, mean=0.26-0.34 for others), so it proves that given maximum priority to the ecosystem services is a comprehensive approach to prioritise both conservation of biodiversity and ecosystem services (Table 4-5 and Figure 4-18). The pressure and threat scenario (PRTH) shows a comparatively minor value for Total Conservation Priority, and a greater Total Nature Conservation priority, when compared to the baseline (BSL). These results highlight the two factors (i.e. current pressure and future threat) as a major concern for nature conservation, since they represent, together, half of the value assigned in the Total Nature Conservation Priority index. The policy option PRTH is, in comparison, the least favourable policy option to follow to conserve biodiversity and preserve the provision of ecosystem services.

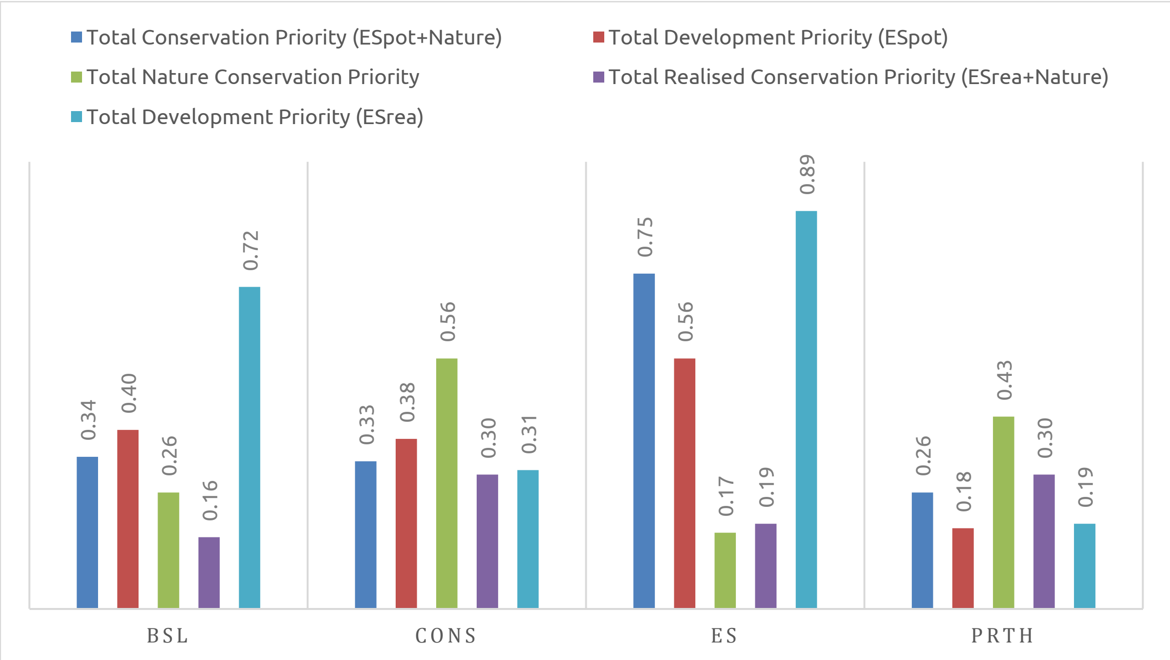

Figure 4-18 Mean values for five bundle indices for the baseline scenario and the three policy options, derived from the Oil Extraction focus area in the Western Amazon

A further analysis only within oil and gas concessions, showing that there is no significant difference between the areas within the concessions and the area as a whole (Table 4-5). This suggests that oil and gas concessions currently do not consider priorities of biodiversity or ecosystem services in their original design and drawing. Thus, new limits for the concessions driven by international and local environmental policy could find a trade-off between exploiting the resource and respecting the areas of highest value for biodiversity and ecosystem services provision.

Table 4-5 Mean values for five bundle indices for the baseline scenario and the three policy options, within the Oil Concessions in the Western Amazon.

indices	Western Amazon section			
	BSL	CONS	ES	PRTH
Total Conservation Priority (ES*pot*+Nature)	0.34	0.33	0.75	0.26
Total Development Priority (ES*pot*)	0.40	0.38	0.56	0.18
Total Nature Conservation Priority	0.26	0.56	0.17	0.43
Total Realised Conservation Priority (ES*rea*+Nature)	0.16	0.30	0.19	0.30
Total Development Priority (ES*rea*)	0.72	0.31	0.89	0.19
indices	**Oil and Gas Concessions Only**			
	BSL	CONS	ES	PRTH
Total Conservation Priority (ES*pot*+Nature)	0.33	0.32	0.71	0.27
Total Development Priority (ES*pot*)	0.42	0.39	0.57	0.18
Total Nature Conservation Priority	0.27	0.55	0.18	0.45
Total Realised Conservation Priority (ES*rea*+Nature)	0.16	0.29	0.18	0.31
Total Development Priority (ES*rea*)	0.72	0.32	0.89	0.20

The areas outside oil and gas concessions are assumed to have no direct impact by the oil activities, but they are not completely free of pressure or threat by other development activities. The previous analysis of the top 17% of the areas of highest value for each bundled index is again of use to determine which strategy may be more efficient and it begins to show the overlap of these top areas with the current oil and gas concessions (Table 4-6).

The Total Conservation Priority index is capped in the ES scenario (mean=0.94), proving the significance of maintaining the potential services particularly in these top-valued areas.

Furthermore, when overlaying these top areas with the oil blocks, the ES scenario has the minimum value of intersection (34%), which releases some pressure over these top important areas for biodiversity (B, CO) and ecosystem services (C, W, HM, T) components of the index.

Table 4-6 Mean values for five bundle indices for the baseline scenario and the three policy options, summarised for the top 17% of area inside and outside oil and gas concessions. Maximum values and percentages are highlighted for each scenario.

indices	Top **17%**, outside concessions			
	BSL	CONS	ES	PRTH
Total Conservation Priority (ES*pot*+Nature)	0.38	0.41	0.94	0.30
Total Development Priority (ES*pot*)	0.50	0.53	0.64	0.26
Total Nature Conservation Priority	0.30	0.72	0.26	0.50
Total Realised Conservation Priority (ES*rea*+Nature)	0.18	0.38	0.24	0.34
Total Development Priority (ES*rea*)	0.76	0.41	0.92	0.25

indices	Top **17%**, intersecting with concessions			
	BSL	CONS	ES	PRTH
Total Conservation Priority (ES*pot*+Nature)	0.38	0.39	0.93	0.29
% of total area	45%	47%	34%	60%
Total Development Priority (ES*pot*)	0.51	0.54	0.65	0.26
% of total area	58%	56%	59%	56%
Total Nature Conservation Priority	0.30	0.70	0.25	0.49
% of total area	69%	47%	38%	60%
Total Realised Conservation Priority (ES*rea*+Nature)	0.18	0.37	0.23	0.34
% of total area	63%	47%	51%	60%
Total Development Priority (ES*rea*)	0.77	0.42	0.92	0.25
% of total area	56%	58%	50%	54%

maximum value within scenario

Nature Conservation Priority (composed of B, CO, PR, TH) is maximised in the CONS scenario (mean=0.72), though almost half of these areas (47%) are located within an oil and gas concession. It is worth mentioning the fact that all of the indices show considerable intersection (34-69%) with oil and gas concessions, which is the main reason of conflict between exploiting the hydrocarbons and preserving nature (Finer et al., 2008). Moreover, none of the modelled scenarios is effective in maximising all the indices, which indicates there is always a trade-off between having one or another priority.

Further analysis of the spatial patterns of the policy options is presented below using a map comparison of the top 17% of areas of Total Conservation Priority (Figure 4-19).

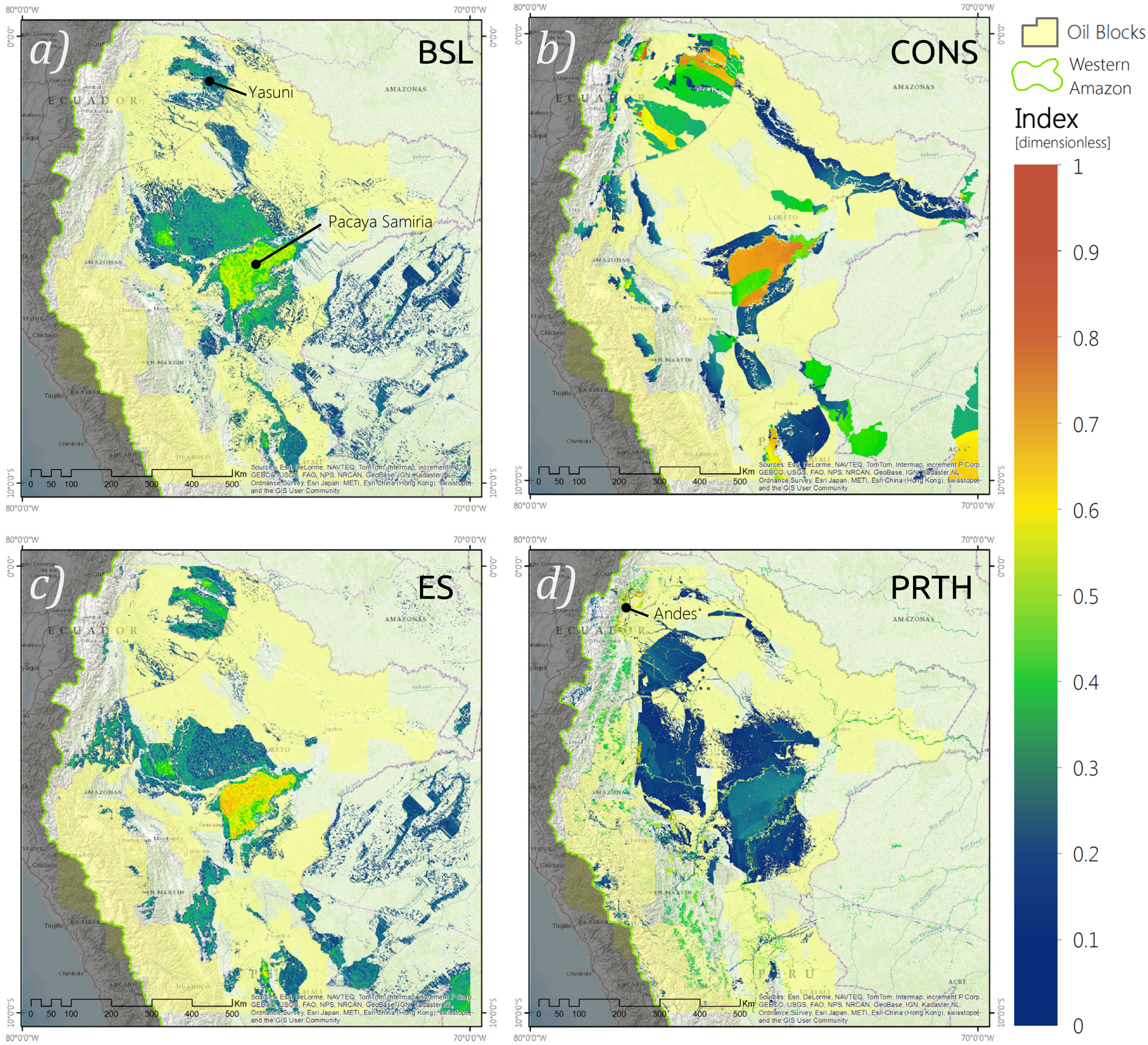

Figure 4-19 Top 17% of Total Conservation Priority Index areas (normalised locally 0–1) for *a)* Baseline (BSL), *b)* Conservation (CONS), *c)* Ecosystem Services (ES), and *d)* Pressure and Threat (PRTH) scenarios and their overlap with oil and gas concessions

The maps comparison show the spatial distribution and scale variability of the top 17% areas with highest values for the Total Conservation Priority Index. The BSL scenario (Figure 4-19*a*) shows high influence of water provision and carbon services, detailing even the flow of the waters downstream carrying their positive influence with this flow and creating a scattered patter of distribution. In contrast, the CONS scenario (Figure 4-19*b*) clearly marks the boundaries of the delphics and biodiversity values, which is an artefact of an anthropogenic design of these limits, although they certainly mark the top priorities in agreement with the rest of scenarios, as the Pacaya-Samiria region and the Yasuni area come up as top priorities.

The ES scenario (Figure 4-19*c*) aggregates into larger pixel groups, which would likely produce more efficient and coherent conservation clusters, which can be proposed as potential new protected areas, if they are not already part of one. Finally, the PRTH scenario (Figure 4-19*d*) is dominated by the peat soils underneath the Peruvian Amazon, which make up for most of the pixel distribution. However, the highest point values within the index are dispersed in the Andean reaches. These clusters are important at the local level, particularly in the Ecuadorian Amazon, where the highest values of the index are localised. This scenario of pressure and threat has the highest overlap with the oil concessions (60%) and, it can be used as an important input in discussion of trade-offs of potential oil development.

A final analysis intersects the top regions for each proposed policy scenario, and it shows the topmost areas that should be declared as NO-GO for extractives. This key message is backed by all the available relevant data and statistics. The intersection of all the top areas in the scenarios yields a total area of 38,000 Km^2 (Figure 4-20), which is only 4% of the total area analysed. On the positive side, 77% of this topmost areas are already included as part of the current protected areas, proving the importance of protected areas in the conservation of biodiversity and preservation of ecosystem services provision (Scharlemann et al., 2010; Tuvi et al., 2011). On the other hand, 31% of the topmost areas are within oil concessions, which pose a potential threat to their conservation in the long run. Note that several protected areas are overlapped by oil and gas concessions, which is contradictory by principle, but it goes up to 89,000 Km^2 of overlap only within this region. Consequently, some of the topmost regions intersect with a protected area and an oil and gas concession at the same time. The Yasuni in Ecuador, as well as the Santiago Comaina and Pacaya Samiria protected areas are the holders of this key areas where extractive activities should be completely avoided.

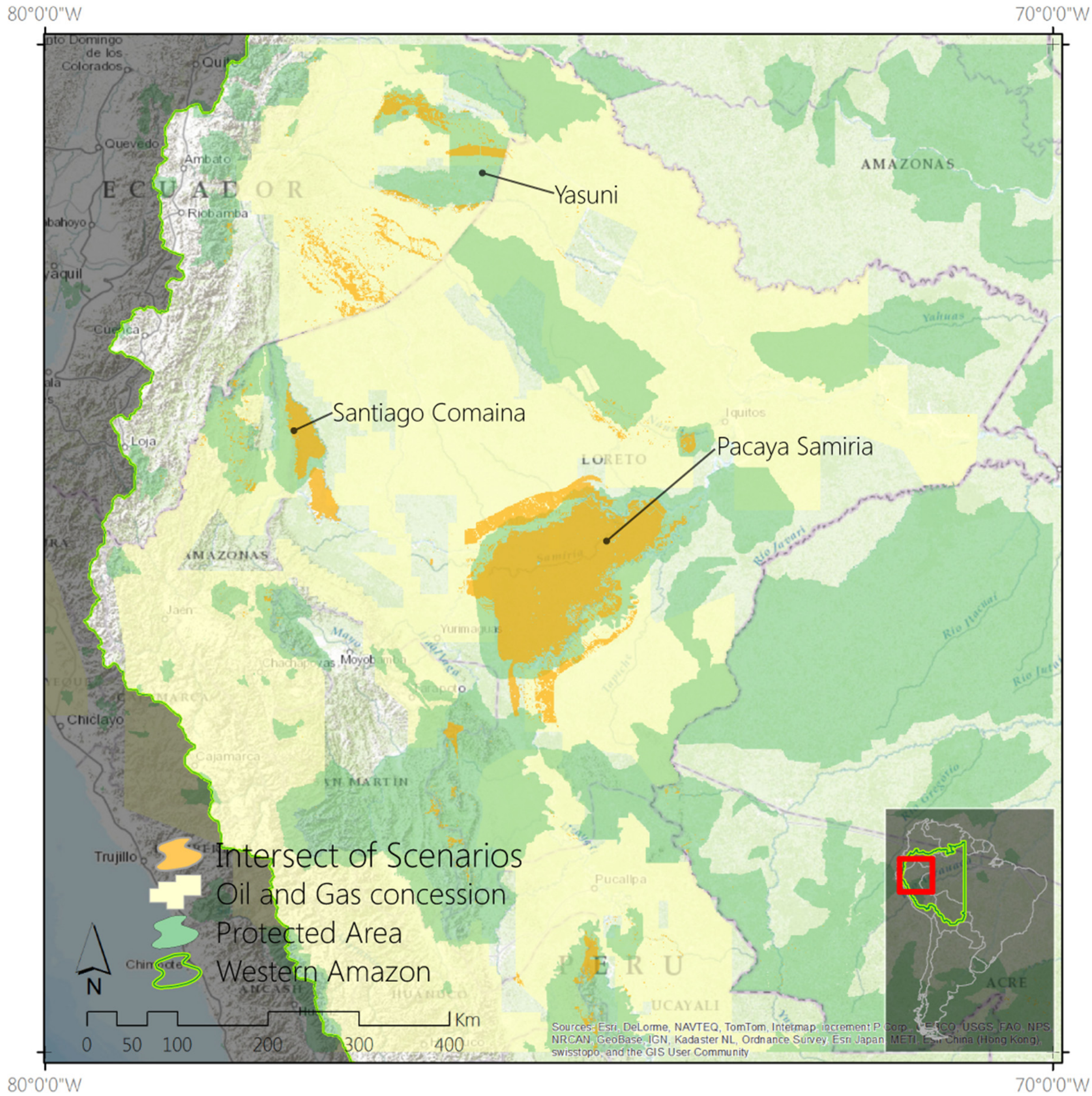

Figure 4-20 Topmost priority areas for Conservation, Ecosystem Services, and Pressure and Threat scenarios, showing their overlap with oil and gas concessions and protected areas

In all cases, the most prominent area to prioritise for conservation is the Pacaya-Samiria National Reserve, which holds carbon stocks of 14,700 Mg C/Km^2 in average, and it has a rate of 15 Mg C/Ha yr of carbon sequestration. As well as being home for approximately 900 taxa of threatened mammals, birds, reptiles, or amphibians currently listed by the IUCN. It has a positive average water balance of 1600 mm/yr, and a calculated average of only 0.04% of human footprint on its waters. Furthermore, the area has no major oil concession overlapping its territory, which makes conservation efforts much more achievable. Nevertheless, being close to the highly active oil extractive area of Loreto, and particularly being downstream, it has already taken a toll in the ecosystem's health by damaging oil spillages in its waters (Soria, 2004).

Ultimately, different strategies of conservation prioritisation yielded these common results which are the key message that could be scaled up to global scale and have a wider more comprehensive view of the issues that extractives pose on ecosystem services and biodiversity. It is thought that only through this process of general observance of patterns and connections, a better understanding of the particularities of ecosystem services can be achieved.

4.6 COMPARISON WITH WA-WIDE MCA

In the previous chapter, I developed a bespoke analysis of ecosystem services and oil impacts for the Western Amazon, using a multi-criteria analysis that yielded illuminating results. In this section, I compared it with the global tool applied to the region (i.e. Co$ting Nature) based on similar datasets but through different algorithms. The purpose was to apply independent approaches and examine the difference in their overall prioritisations.

They both indicate many of the same important areas where ecosystem services are being provided to people or have the potential to do so. However both approaches only overlap in 30% of the masked top areas. When analysing the oil concessions that overlap the Total Conservation Priority Index, TCPI, (from Co$ting Nature), 28% of the top areas overlap for this index within an oil concession, whilst for the Ecosystem Services Index (ESI), (from the previous chapters Multi-criteria GIS Analysis) overlaps only on a 7% with oil and gas concessions. The spatial patterns of these top areas differs significantly, due in part to the weighting process that each one follows, but it seems to be highly influenced by the carbon value index in CN, which is dominant and brings a good part of the Peruvian Amazon to the top group (Figure 4-21*a*). In comparison, the water services and protected status of the north region of the Amazon in Brazil is the main driver of the ESI index (Figure 4-21*b*)

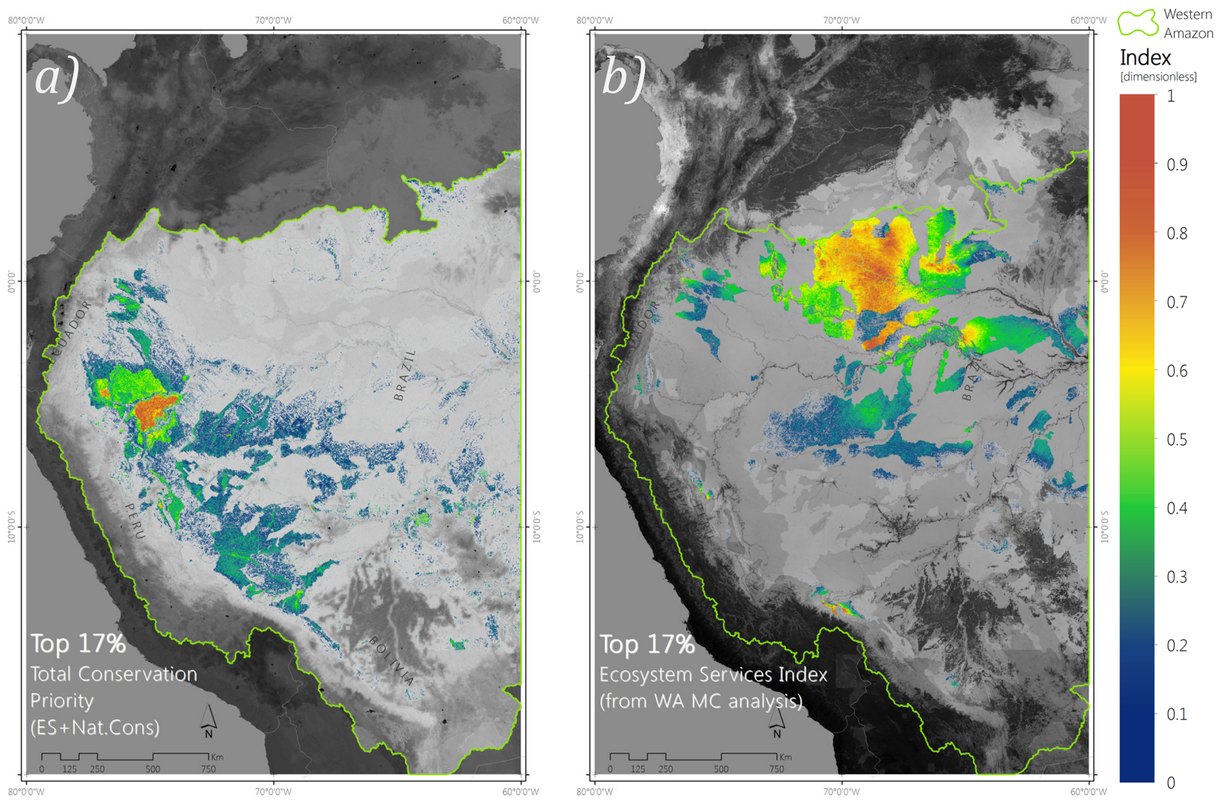

Figure 4-21 Top 17% area of *a)* Total Conservation Priority Index, from Costing Nature, and *b)* Ecosystem Services Index, from Multicriteria GIS analysis, normalised regionally (0-1)

Even though both approaches used similar datasets, to ensure comparability, they used different perspectives of prioritisation. The bespoke analysis approach was focused on showing the specific impacts of oil extraction, so those localised high levels of impact of the oil industry were weighed heavily on those particular calculations, whereas Co$ting Nature shows broader impacts than just the oil and gas industry's. CN allows to place in context all the considerable impacts on ecosystem services. Furthermore, the TCPI calculation takes into account "positively", in a mathematical sense, both pressure and threat, leading to high values over the oil and gas concession as both the loss of ecosystem services and nature risk are high in the Ecuadorian and Peruvian Amazon (Figure 4-21*a*). On the other hand, ESI takes areas of oil activities in a negative way, both mathematically and in terms of risk of loss of services, thus producing priority areas in the Brazilian and Colombian sections of the Amazon, where oil activities are neither active nor planned for the near future (Figure 4-21*b*). These comparison confirms that two different approaches can lead to similar conclusions on a statistical level. However, it is very important to look at the spatial distribution and the basic construction of the approaches in order to infer the differences and, rather than choosing one or the other, understand the strengths and weakness that each of them presents.

4.7 CONCLUSIONS

Several key conclusions were derived from the results obtained in this evaluation of different strategies for the prioritisation of environmental conservation efforts. Although the study is focused on the Western Amazon, the observations could be adapted to other places in the world, where similar concerns are raised. The following conclusions are proposed based on the elements observed in this study and are presented here as a proposal for further discussion and future research.

- Prioritisation depends on what one holds as valid or true and, based on that, what becomes important and worth conserving. Consequently, a modelling tool that maps these priorities helps this process in a more spatially explicit manner. These type of results help to quantify objectively the conservation priorities within a region. At the end of the day, conservation priorities are a subjective decision, which we can only try to make more objective by providing appropriate and detailed data in ways that can be used in policy formulation.

- When looking at the current conservation efforts in the Western Amazon, it is very important to avoid duplication of initiatives. Reflecting on the spatial overlapping of similar conservation priorities can shed light on areas that lack presence of protected areas or that are poorly represented. Sharing openly this information may help to better decision making in new proposals of protected areas.

- Getting to know the current status and health of the ecosystems at global level is one of the, maybe the most, important tasks carried out by the MA scientists (MA, 2005). Modelling tools, such as Co$ting Nature (CN), may facilitate this process immensely, since this study can be scaled up to global extent. Although, one of the caveats to remember is that CN is based on available global information, so there may problems in terms of lacking some relevant data and not being able to represent the variability of a parameter due to the coarse resolution of the input data.

- Two models for ecosystems services may yield different results based on the quality and detail of the data used to parameterise them, but also based on the approach and assumptions that the modeller makes. As a consequence, the results are only as good as the data used, and they can only do so much to inform and represent the reality of ecosystem services. Indeed, it is up to the users of this information, what they can do to fulfil the objectives of conservation and how to best prioritise their efforts.

- The intersection of the different scenarios proposed for conservation prioritisation helped discerning the topmost areas that are proposed to be a no-go zone for extractives. Taking into account the benefits these topmost ecosystems provide should overturn any decision to develop them for resources extraction that will impair the ecosystem services provision.

- The current protected areas system already covers a good portion of the found topmost areas, so the finding of this study would help to strengthen the case of conserving these areas and make sure that they are not just 'paper parks' that are not properly protected. Furthermore, the remaining topmost areas that are not under protection could be the basis to propose the expansion of the protected areas system to reach the Aichi targets of protection of the 17% of land relevant to ecosystem services and biodiversity for 2020.

- On the other hand, the topmost areas prioritised for conservation and the current protected areas are also overlapped and surrounded by oil and gas concessions, so careful attention should be paid to the proposed developments by the governments of the region and the results of this study can help to express spatially the contradictory situation of areas that should be directed to conservation.

CHAPTER 5

ANALYSING THE REGIONAL SIGNIFICANCE OF EXTRACTIVE INDUSTRIES ON THE WATER QUALITY OF THE ANDES AND WESTERN AMAZON

5.1 OVERVIEW

In this chapter, I analysed the regional and local significance of the extractive industries (mining, and oil and gas) on the water quality of the Andes and Amazonia in Colombia, Ecuador and Peru. The WaterWorld model (version 2.91, www.policysupport.org/waterworld) was used to create predesigned scenarios for the development of extractives based on ground and remotely-sensed data. They were examined in a separate scenarios. The impacts on water quality (measured as the human footprint on water, referred above in section 4.2.4.2) were analysed at the regional scale for the Western Amazon and also focused at the local scale on: the Grand Coello basin, in Colombia, which is highly impacted by mining now and with imminent new developments, and the Tiputini River, in Ecuador, where oil extraction is a current pressure and a continuous future threat for the area. The study first established a baseline scenario of all current human footprint, including extractives and all other anthropogenic influence on water quality. With this baseline established, it was then possible to model realistic scenarios of mining and oil and gas development at the regional scale and with further detail in the mentioned case studies, where observed data was used for validation of the results.

5.1.1 THE SIGNIFICANCE OF EXTRACTIVES ON WATER QUALITY

The significance of extractives industries is normally addressed in terms of their contribution to the national economies (Simoes and Hidalgo, 2011) whilst their impacts on the environment and how significant these can be on ecosystems are rarely included in the calculations of benefits. In this chapter, I focus on environmental impacts of extractives, specifically on water quality, that may be produced for their development. A comprehensive mapping of mining and oil and gas concessions and sites of production within them for the whole Andes and Amazon has not been done before with enough detail to yield useful results. Global studies have contributed to understand mining risks (Miranda et al., 2003) and fossil fuels impacts on biodiversity and within protected areas (Butt et al., 2013; Osti et al., 2011), as well as participatory GIS has helped to raise awareness of the conflicts of extractives around the world (EJOLT, 2014). However, these global databases have significant room for improvement. In effect, this improvement was done for the focus countries using local expert knowledge in combination with data from official agencies, in order to develop a realistic baseline to support the proposed development scenarios. The significance of extractives on water quality for the Andes and Western Amazon was assessed quantitatively in terms of percentage and extent using a modelling tool parameterised with up to date datasets.

5.1.2 DISTRIBUTION OF MINING CONCESSIONS IN THE ANDES AND OIL CONCESSIONS IN THE WA

The planned concessions for mining and oil and gas are distributed across the whole region of study. In general terms, mining concessions are concentrated in the mountainous areas of the Andes, whilst the oil and gas concession tend to be in the Amazonian lowlands. Based on the information published by national agencies and NGOs that work in this area (Servicio Geologico Colombiano, 2014; Agencia de Regulacion y Control Minero, 2012; IBC, 2009), the mining concessions were calculated to cover 5% of Colombian land territory, 22% of Ecuador's continental territory, and 9% of Peru's. The average size of a concession in the three countries is 5 Km^2, varying from concessions of 1 Ha. (0.01 Km^2) to a maximum of 2,000 Km^2 in one single mining concession in Colombia. The status of each concession varies from no activity to exploratory and extractive activities, depending on how the government agency in every country manages the concession. Nevertheless, all the concessions have the potential to become mines at some point in the future. For oil and gas concessions, the land coverage is higher, due to the big size of each concession. The average size of an oil concession within the Western Amazon was calculated to be 3500 Km^2, and in total, they cover 55% of Colombia, 25% of Ecuador, and 44% of Peru. This was calculated from official data published by the state oil companies in the countries (ECOPETROL, 2010, PETROECUADOR, 2010, PERUPETRO, 2010). Once again, the current status of the concessions fluctuates from 'unassigned' and 'under negotiation', to 'explorative' and 'exploitation'. All of the concessions are allocated by the central government, or the designated agency to either national or international extractive companies that enter a bidding process based on the preliminary information provided to start exploratory activities and eventually the extraction of hydrocarbons (SHE, 2014).

Environmental concerns are nowadays carefully considered, so an environmental licence granted by the Ministry of Environment in each of the three countries is necessary before any extractive activity starts (OLCA, 2013). Exploratory activities are treated more lightly, despite having a much more extensive impact than extraction as is the case with widespread seismic lines and exploratory drilling carried out to determine the potential reserves of oil or gas that lie underground (Orta-Martínez and Finer, 2010, Peepre et al., 2004).

Mining activities are of both industrial and artisanal nature, and there is a marked difference in the applied techniques and their environmental impacts, as it was earlier discussed in section 2.8.2. In general, large scale mining has a higher potential impact, hence it is more regulated, and available information on concessions and extractive activities is more reliable. In contrast, artisanal mining, though small and medium in scale, can pose equally significant threats to the environment due to ineffective regulation, poor infrastructure and unsafe practices (Telmer and Veiga, 2009). The number of artisanal activities competing for the same resource in a relatively small area creates a high concentration and intensive extraction (Ashe, 2012). Even more, the extractive techniques applied are rudimentary (gravity and amalgamation with mercury), which combined with inadequate care of the residuals place a threat for miners as well as populations living and depending on water resources downstream (Veiga and Meech, 1995). Lastly, these artisanal activities are, in many cases, operating illegally and without a proper environmental licence, hence reliable information of location and contamination extent of these activities is difficult to assess (Telmer and Veiga, 2009). In some cases, the impacts are devastating in terms of deforestation and water pollution, such as the case of Madre de Dios, Peru (Ashe, 2012; Swenson et al., 2011). Given the difficulties and limitations of predicting the growth and impacts of artisanal mining, I concentrated this part of the research on the mining concessions and mining sites that are legally recognised by the national agencies, providing a source of information upon which to develop scenarios.

Oil extraction can only be carried out by big extractive companies due to the infrastructure, technology and investment needed, and the larger the project, the more cost efficient should be. Today, the environmental regulations on oil and gas production are strict, at least on paper, but the enforcement of these regulations in remote areas where exploitation occurs has proven difficult. In fact, several contamination events have been documented, such as the Texaco operations in Ecuador (Amazon Watch, 2009, Buccina et al., 2013) and the Corrientes River in Peru (Orta-Martínez et al., 2007), where the impacts could have been minimised if appropriate planning and environmental considerations had been taken into account before the start of extractive activities, as was discussed in Chapter 3 of this thesis.

In summary, mining concession follow a local size, and mountainous oriented pattern, whilst oil and gas concessions are of regional size and focus on the lowlands (Figure 5-1).

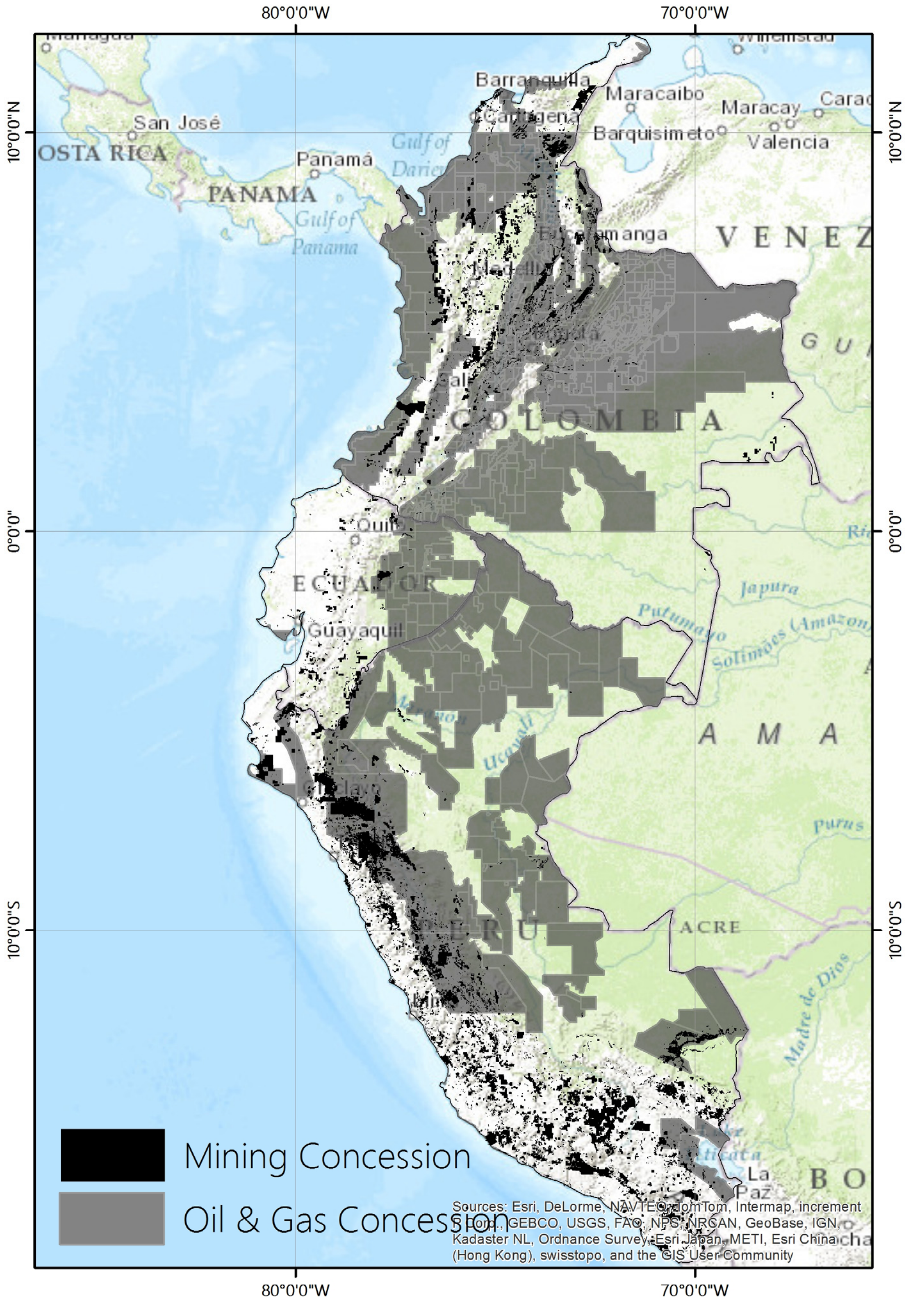

Figure 5-1 Extent of mining and oil and gas concessions in Colombia, Ecuador and Peru

5.1.3 The Grand Coello Basin and Mining extractives

The Coello and Combeima rivers together make the Grand Coello Basin. They run through the Colombian Andes before reaching the Magdalena River. The Grand Coello has a total catchment area of 1,800 Km^2 and 125 Km of flow length (Cortolima, 2005). The source is located in a *paramo* ecosystem above 3800 m, and it flows down through a mountainous region of cloud forest, reaching an extended floodplain at 300 m above sea level (Colombia Solidarity Campaign, 2013). This 3,500 metre range of altitude allows for a variety of habitats to take place along the basin. The city of Ibague is located in the lower section and it depends directly for its water consumption on the Combeima River. In general the whole region, with more than 500,000 inhabitants, depend on water provision for their basic needs, such as human consumption and agricultural production at small and large scales, which currently account for 83% of the land use in the region (USOCOELLO, 2013, Candelo et al., 2014).

The Nevados National Park is partially included in the basin and it is located in the north area of the basin. The national park is an important source of clean water that comes from the area and even glaciers above 4000 metres. Through the baseline analysis, up of 4% of the annual runoff was calculated to come from snow melt in the upper catchments, though this contributions decays quickly downstream. The annual water balance for the basin is positive all over (range 300-3300 mm/year) with an average of +1700 mm/year. An approximate 6% of this comes from fog contributions captured by trees in the cloud forest belt of the catchment. The snow and fog contributions decay to only represent <2% by the time the Coello reaches Ibague.

Mining concessions cover more than 50% of the area of the catchment, and represent 179 mining permits, which vary in their stage of development. Nevertheless, most of them are likely to be developed depending on the funding and resources of the permit holder, though global prices of precious metals can easily tip the balance towards extractive development (Specht, 2014). The Citizen Action Negotiation process (CAC for *Conversatorio de Accion Ciudadana*) is a collective action initiative formed in the Grand Coello aimed to look for a more sustainable development by including and informing all stakeholders. It combined legal and social mechanisms with hydrological modelling and negotiation supporting tools to develop improved access to locally relevant information and hydro-literacy amongst all of the stakeholders. The CAC development in this basin has been supported by the CGIAR Challenge Programme on Water Project AN3 on Benefit Sharing Mechanisms for the Andes (Mulligan et al., 2013). Compensatory protection of important ecosystems, changes in the management of production systems for agriculture, improvement of access to clean water and appropriate sanitation, are amongst the main discussion points to ensure sustained high quality water provision as the region develops (Candelo et al., 2014). Ultimately, this study can contribute to the analysis and discussion of an informed process of decision making through the use of advanced hydrological modelling tools to project impacts of different scenarios of change for this basin. This preliminary description of the situation of the basin allowed to portray in Figure 5-2 the components of relevance, showing high coverage of mining concessions in the head waters, whilst most population and other activities occurred downstream.

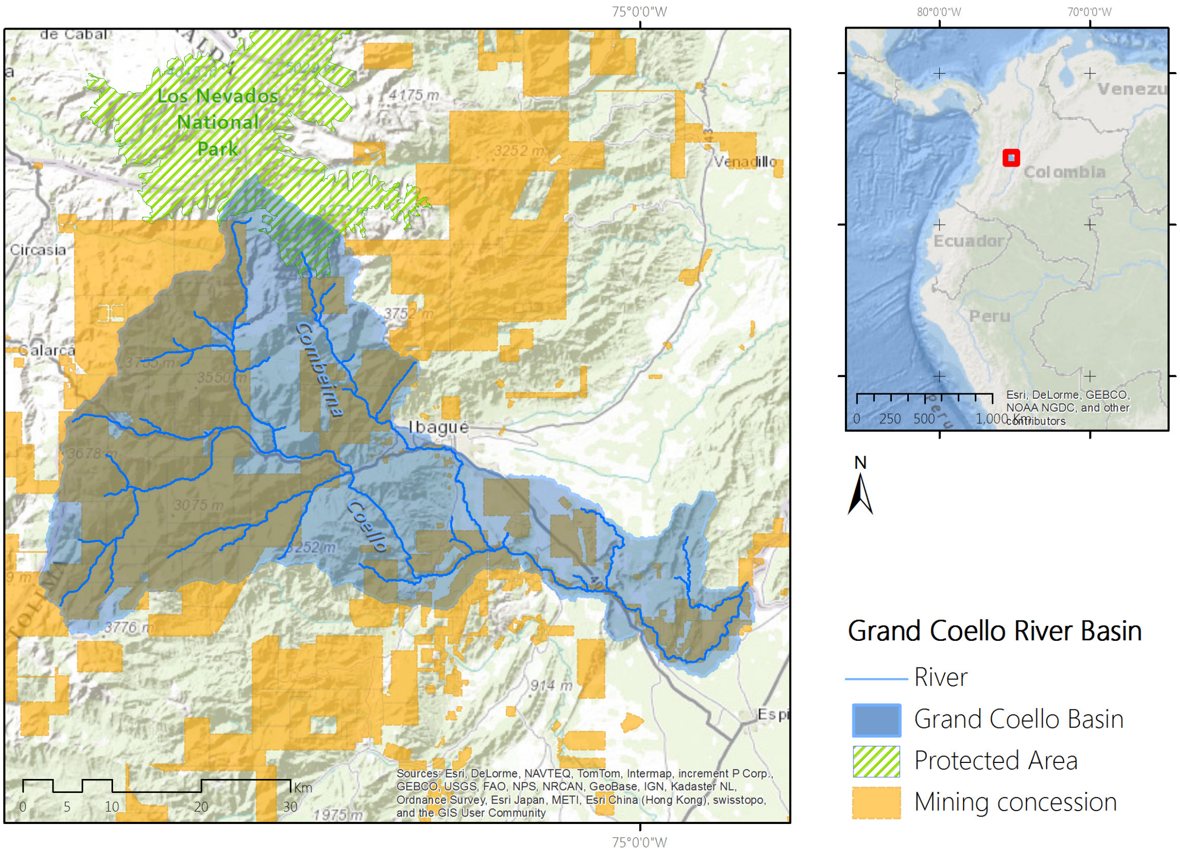

Figure 5-2 Grand Coello Basin in the Andes of Colombia, showing the overlap of mining concessions with the headwaters of the Coello and Combeima Rivers and protected areas in the region

5.1.4 The Tiputini River and Oil Extraction

The Tiputini River is part of the Western Amazon basin. It flows across the lowlands of Ecuadorian Amazon until it joins the Napo River and eventually the Amazon River. Its upper reaches are no higher than 400 metres and it flows down to 200 metres above sea level when it pours into the Napo River. It flows in a West to East direction along a fairly flat region of lowland rainforest. This creates hundreds of meanders and a combination of *varzea* and *terra firme* forest formations that are home to a large number of species (Oxford et al., 2012). Furthermore, the basin is a main part of the Yasuni National Park, widely recognised as a high biodiversity spot (Cisneros-Heredia, 2006, de la Torre et al., 2009, Bass et al., 2010).

Oil concessions overlap approximately 80% of the basin. Moreover, the oil and gas concessions extend for a vast area of the Ecuadorian Amazon, and they overlap with the Yasuni National Park, in more than half of its one million hectares (1,000 Km^2) of extension (Figure 5-3). These statistics show the lack of appropriate spatial planning that led to these contradictory situation where an internationally important protected area is heavily covered by blocks for industrial scale extractive activities. Only the southern part of the park is reserved as an "untouchable" area for the voluntarily-isolated groups of the Waorani indigenous nationality, though this area also has some overlaps with the current oil concessions (Pappalardo et al., 2013).

The Tiputini, along with the Cononaco River are thought to be sources of clean water provision for the indigenous communities living in the forest. The area is an important store of carbon and significant sequestration of CO_2 as evidenced in the discussion around the Yasuni-ITT proposal (sections 2.6). The potential of this area's ecosystem services in terms of water provision, natural hazard mitigation and nature-based tourism were recognised to be importance in the Co$ting Nature analysis of Chapter 4 (section 4.4.2). Clearly individual new operations require EIAs (Environmental Impact Assessments) and SEAs (Stratetegic Environmental Assessments) to operate at the local level; it is not the focus here to replace those but rather to look beyond individual developments to the connected and multiple developments that are taking place at the landscape scale in order to understand their cumulative impact.

The main information gathered to determine the components of the current analysis are put into general context through the map layout in Figure 5-3 that shows the mentioned 80% coverage of oil concessions overlaying the basin and the various intersections with the Yasuni National Park.

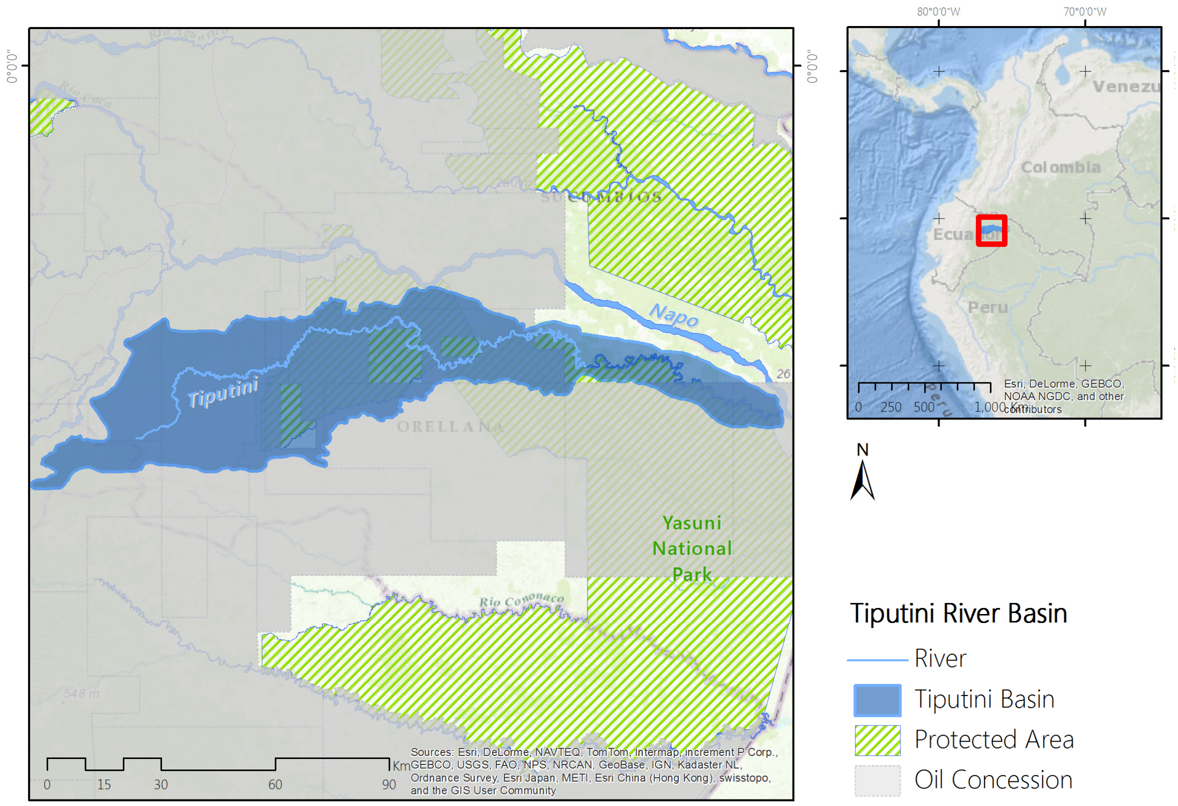

Figure 5-3 Tiputini Basin in the Ecuadorian Amazon, showing the overlap of oil and gas concessions and protected areas in the region

5.2 Methods

5.2.1 Modelling with WaterWorld

Obtaining a comprehensive and historic database on climatological and environmental variables at a national and catchment scale in areas with a poor history of data collection is not an easy nor a practical task for the whole of the Andes and Western Amazon. Remote sensed data, even at a global scale, has proven to be a reliable and efficient way to provide up-to-date and scale relevant information to support and improve environmental modelling efforts (Bastiaanssen et al., 2005, Roujean et al., 1992). The WaterWorld model (version 2.91) was used for the baseline and scenario analyses in this chapter. WaterWorld is a web based modelling tool that enables sophisticated but rapid assessment of the spatial hydrological baseline of an area, and the application of diverse change scenarios, including for extractive industries development. This tool has been widely applied and tested and has proven to be of use particularly in areas that lack appropriate data for ground based characterisation of hydrology or for problems at more policy-relevant scales where ground data become less relevant. The system provides all the parameters for the model application using global databases but with the flexibility to upload and replace the provided data with improved information if it exists (Van Soesbergen, 2013; Van Soesbergen and Mulligan, 2013). The extractive industries scenario is applied for this thesis separately for mining development and oil and gas extraction. The previously mapped mining and oil and gas concessions are projected to be developed by a determined percentage and the impacts of this development on WaterWorld's water quality metric are then measured and compared with the baseline simulation representing current conditions. In order to better understand this process and the assumptions taken into account, one must first understand the model behind the tool, the parameters it takes to run, and the results that are produced to represent water quality in the Andes and Western Amazon.

5.2.2 The FIESTA model as part of THE WaterWorld PSS

The model behind WaterWorld is based on the Fog Interception for the Enhancement of Streamflow in Tropical Areas, FIESTA, model (Mulligan and Burke, 2005) which was developed to simulate the hydrological baseline of mountainous catchments spatially for small catchments (10 hectares) to the national scale, in Costa Rica (60,000 Km^2). It was later adapted to be applicable globally, by providing appropriate data since it is a physically based model that can be readily applied without calibration. It is not calibrated for one specific location, which allows for its application anywhere globally, (Mulligan, 2012d). It is a gridded model with a monthly temporal resolution and simulates based on a mean climatology for 1950-2000 implemented largely in Python, GDAL, SciPy and other open source GIS tools. The model calculates the surface water balance for each cell and then routes flow downstream according to the D8 algorithm for hydrological models, which takes one cell and considers the eight neighbours around it, to determine in which direction the water falling in the central cell will flow. Ultimately, the model creates the network of flow directions of every cell to its steepest downslope neighbour. Version 2 of the model has no subsurface component, so downstream flow is calculated using local water precipitation (rainfall + fog+ snowmelt) minus actual evapotranspiration routed downstream (Mulligan, 2012). The water quality metric used by WaterWorld is the human footprint on water quality (HF, Figure 5-4), which was described as part of the Water Services on Chapter 4, and it is also of relevance for this chapter.

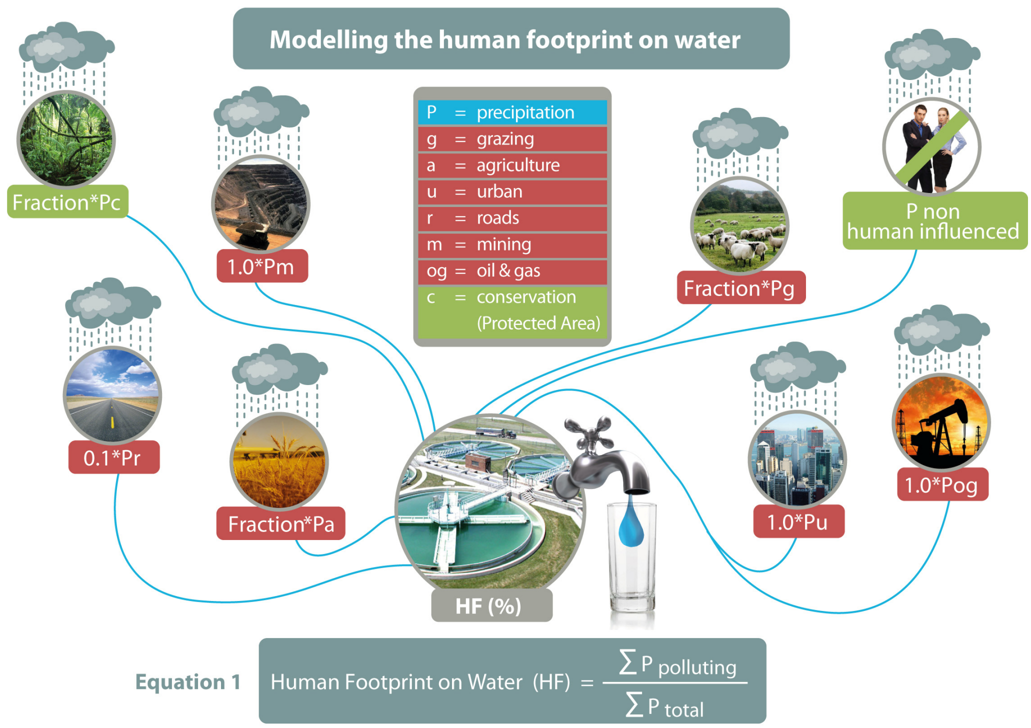

Figure 5-4 components of the Human Footprint on Water Quality (adapted from Mulligan, 2009b, graphics: D. Zurita)

As stated before, it is calculated globally for the baseline and it includes for its calculations the weighed contribution of all mapped human activities that affect water quality: grazing (g), agriculture (a), urban areas (u), roads (r), mining (m), and oil and gas (og). They all pollute depending on the assigned weight or fraction, whilst protected areas or zones of conservation (c) contributes by diminishing the human footprint. The diagram in Figure 5-4 is once again of relevance to point out the higher weights of 1.0 (compared to 0.1 for others) that is assigned to mining and oil and gas activities in the calculation of the HF.

5.2.3 DATA INPUTS AND THEIR IMPROVEMENT

The SimTerra database is the mainstay of the Co$ting Nature and WaterWorld policy support tools used in this thesis. The 500+ global layers in the database are the result of a comprehensive effort to develop and collect robust global datasets of all environmental and socially relevant variables at two operational resolutions, namely 1 Km^2 and 1 Ha, both used within this chapter to accommodate the scale of the catchment area. A total of 155 datasets are needed to parameterise the model. The most significant are the climatological variables, derived from WorldClim (Hijmans et al., 2005) and land cover data (DiMiceli et al., 2011; Sexton et al., 2013), as well as separate layers for cropland, pasture, roads, mining, oil and gas, protected areas, some of which were improved with collected information at the local and regional scales, as described in the following sections. A complete list of the input datasets can be found in Appendix G.

OIL AND GAS DATA

For this study, new datasets for mining concessions, current mining sites, oil and gas concessions, and the presence of oil and gas wells were independently collected, and in some cases digitised from raw data, then corrected and standardised, in order to properly represent the current status and potential scenarios of extractive development in the Andes and Western Amazon. The information published by the State Oil Companies for oil concessions at the national level was obtained in GIS format (.shp) for Colombia, Ecuador and Peru, (ECOPETROL, 2010, PETROECUADOR, 2010, PERUPETRO, 2010). They needed to be corrected and converted into raster format to be used as parameters for the model. In the case of Ecuador, the collected dataset was merged with an updated version to include the oil blocks that were open to bid in the 2012 oil round XI, currently managed by the Ecuadorian Hydrocarbons Secretary. This included a further 13 blocks in SouthEastern Ecuador, bordering the Peruvian concessions and planning to be connected via the Northern Peruvian Pipeline system (DeloitteLLP, 2014). In summary, all current concessions were included, and will be subject of modelled development, as explained further below in the section 5.2.4. Figure 5-5 shows an example of the improvement of using the collected datasets and local understanding over the area instead of global datasets. In this case, the area is currently under exploitation by Petroecuador. This is an atypical oil concession, since it is part of the state-owned company, so it does not appear in global databases, but in the field it has been a site for intense oil extraction for over four decades.

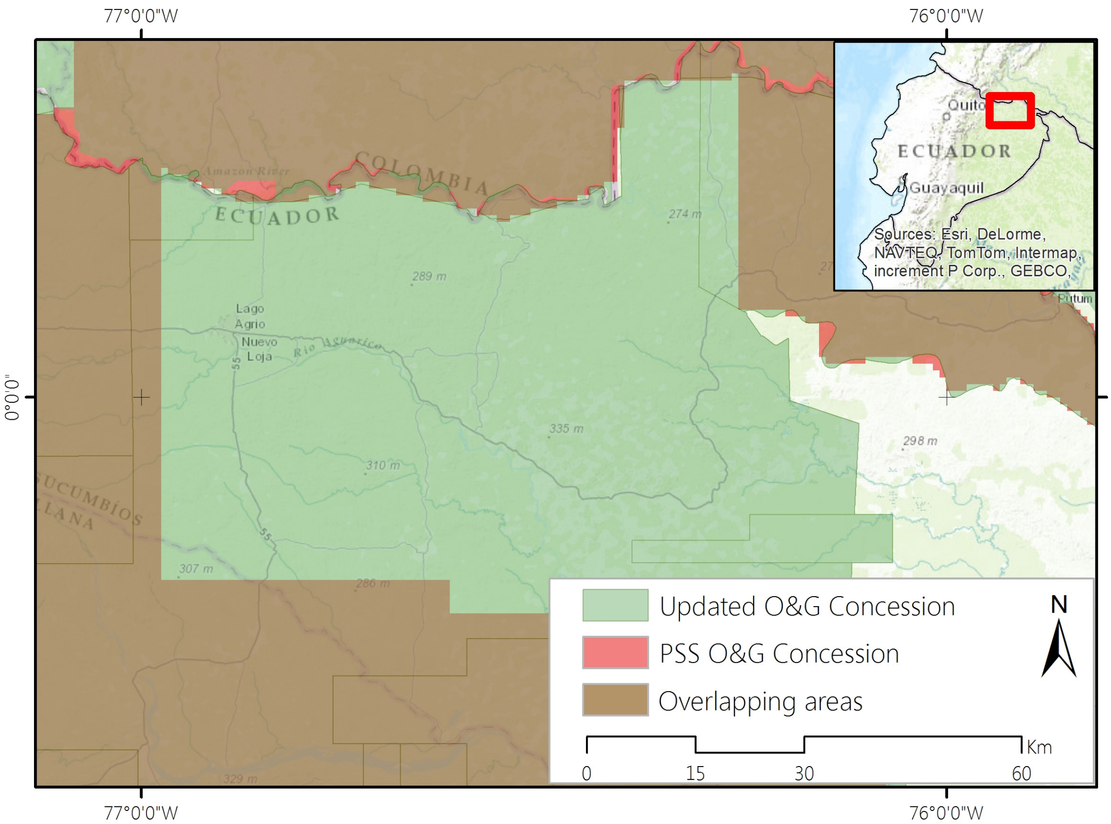

Figure 5-5 Area of data improvement for oil and gas concessions dataset, showing a detail in NE Ecuador

In a similar manner, the oil and gas wells layer was revised, updated and corrected with information provided, as a vector point shapefile, by unpublished sources of the state-owned oil companies (Ecopetrol in Colombia, Petroecuador in Ecuador, and Perupetro in Peru). In order to include this information within the model, it was converted to a suitable raster, with one pixel representing each well, assuming that the area of local influence is equal to the pixel size (1km). The presence and correct location of the well implies that there is a human footprint at that location that will be part of the flow network and potentially transported downstream. When working at 1 Km^2 resolution, some areas of oil exploitation present more than one (up to 6) wells within one pixel, which was still placed as one pixel since these datasets are included in the model as Boolean maps, and it is assumed that this concentration of infrastructure does not make a significant difference at the regional scale. Nevertheless, these wells are better represented when working at 1 Ha resolution, where the pixel size allows to better show this type of oil concentrated infrastructure.

MINING DATA

The mining concessions dataset was improved with information from both official and non-governmental sources. The Colombian Geological Service, previously known as National Institute of Geology and Mining Research, INGEOMINAS, is in charge of producing and updating the cartography of geological resources (Servicio Geologico Colombiano, 2014), and together with the recently created National Mining Agency, have published the Colombian Mining Cadastre (Sistema de Informacion Minero de Colombiano, 2009), which was used to improve the mining concession data for Colombia. In Ecuador, the recently created Mining Control and Regulation Agency, ARCOM, published the National Mining Cadastre (Agencia de Regulacion y Control Minero, 2012), based on the information of the National Institute of Metallurgical, Geological and Mining Research, INIGEMM. This cadastre was used to improve the mining concession data. Similarly, the information from the Mining Cadastral Geological System (Sistema de Informacion Geologico Catastral Minero, 2014) was used to improve the mining information for Peru. This information was provided by the Geological, Mining and Metallurgical Institute INGEMMET, of Peru (Instituto Geologico Minero y Metalurgico, 2014).

The current mining sites inside, and sometimes outside, of the concessions is a much more difficult dataset to obtain or map at a national level. Some relevant datasets were obtained for parts of Colombia and others in Peru, where the mining activities have had a longer history. However, this information is much localised and not relevant at a national level, thus the global information on mining sites, available in the PSS database (Mulligan, 2013), was used along the rest of datasets. This dataset is based on the USGS GlobalGIS dataset (USGS, 2007) and likely represents only part of the current network of mining sites.

5.2.4 Running a hydrological baseline for the Western Amazon and Andes

Similarly to the Co$ting Nature environment, WaterWorld is hosted within the Ecoengine platform, which is the computerised framework that hosts the models. Although it is applicable globally, it works one tile at a time, so considerable GIS post-processing was needed to yield the needed results. The tile size depends on the resolution of the analysis. Thus, at 1 Km^2 resolution, the tile size is 10 x 10 degree in longitude and latitude; whilst at 1 Ha, the tile is polygon of 1 degree per side. This chapter works initially at a regional scale, and includes the two tiles between the boundaries of 70° and 80° West from Greenwich, and 10° North and 10° South from the Equator (Figure 5-6*a*). Most of Colombia, Ecuador and half of Peru are included in this regional approach, encompassing the regions of interest from the mountainous Andes to the lowlands of the Western Amazon.

This chapter then focuses at a local scale on two relevant basins: the Grand Coello in the Andes of Colombia, and the Tiputini basin in the Ecuadorian Amazon. For these two cases, the resolution of the simulation is higher, at 1 Ha, thus elevating the detail at which results can be obtained and analysed.

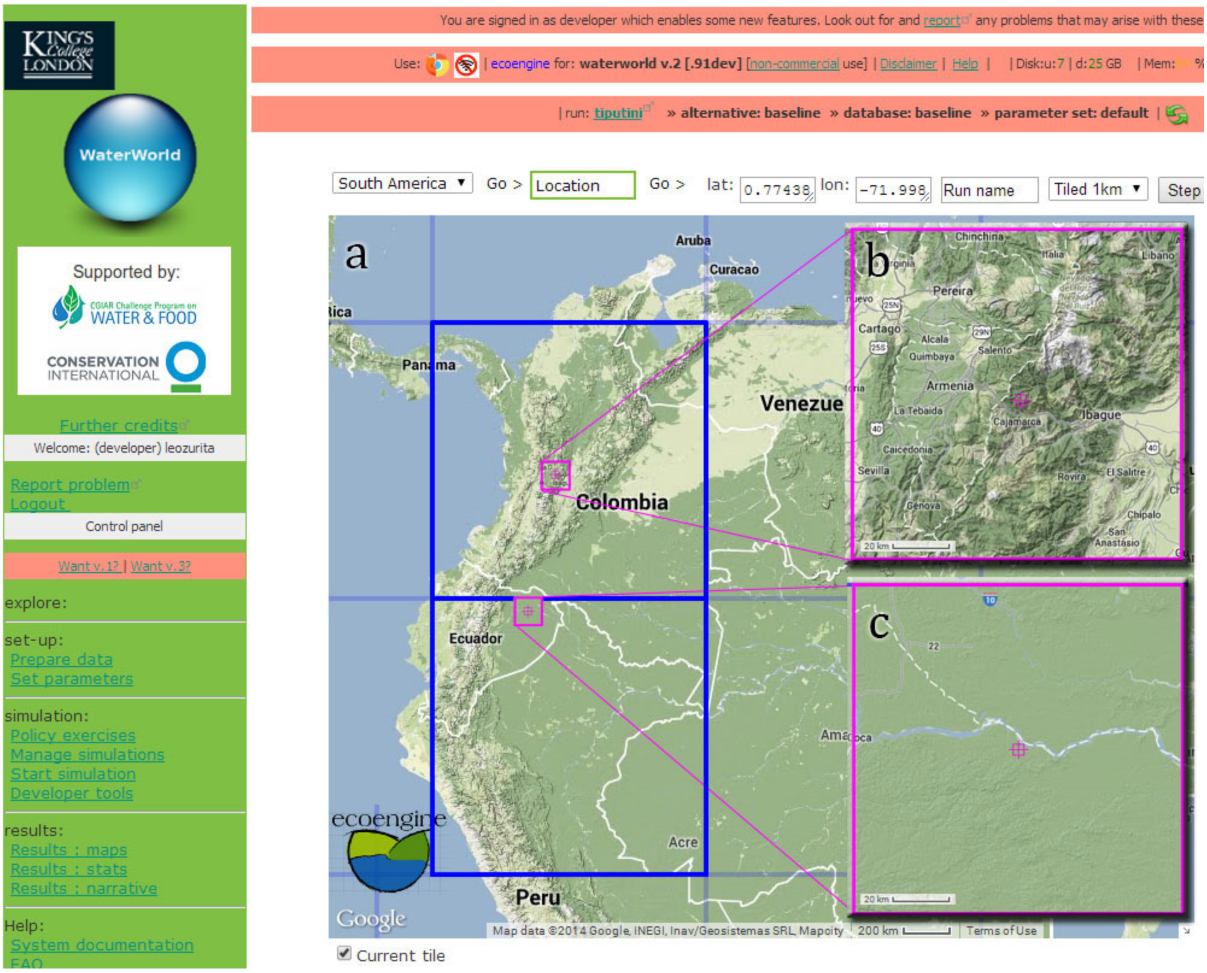

Figure 5-6 Tiles of study for *a)* Andes and Western Amazon, *b)* the Grand Coello basin, and *c)* the Tiputini basin, from the WaterWorld policy support system

The area of interest of the Grand Coello comprises the Coello River and Combeima River basins, and it includes current mining sites and future mining concessions to be developed. It is all encompassed within the one-degree tile between 75° and 76° West of longitude, and 4° and 5° North of latitude (Figure 5-6*b*). The portion of the Tiputini basin with high influence of historic oil extraction and heavily covered by oil concessions is included in the one degree between the longitudes of 76 and 77 West, and the latitudes 0 and 1 South of the Equator (Figure 5-6*c*).

Before running the model, all the input datasets must be properly included within the system. For both resolutions, SimTerra datasets are provided within the PSS. Additionally, the improved information described above is used to replace the corresponding SimTerra maps by converting them to the tile system for the area of study of this chapter. The main input parameters that feed the model are listed in Table 5-1, whilst a full complete list of all parameters can be found in Appendix G, and a further description of the WaterWorld model is included as Appendix H.

Table 5-1 Main input parameters for the WaterWorld policy support system in the context of the Andes and Western Amazon.

Parameter	units	Reference
Cover of bare ground	fraction	Mulligan, 2013
Cover of herb-covered ground	fraction	Mulligan, 2013
Cover of tree-covered ground	fraction	Mulligan, 2013
Elevation	metres	Lehner et al., 2013
Local drainage direction	directions	Lehner et al., 2013
Mean annual cloud frequency	fraction	Mulligan, 2006
Mean monthly precipitation	mm/month	Hijmans et al., 2005
Mean monthly temperature	mm/month	Hijmans et al., 2005
Mining concessions	unique ID	INGEOMINAS, 2008; ARCOM, 2012; INGEMMET, 2013
Oil and gas concessions	unique ID	ECOPETROL, 2010; PETROECUADOR, 2010; PERUPETRO, 2010
Population density	persons/km2	Bright et al., 2008
Presence of mines	unique ID	Mulligan, 2010a
Presence of oil and gas wells	unique ID	Mulligan, 2010b
Roads	type	FAO, 2006
Urban Areas	unique ID	Schneider et al., 2009

The main inputs analysed in this chapter are those related to water quality, such as land cover and land use data and the digital elevation model, which constitute the basis to develop the local drainage direction network, which points the flow direction of water and helps mapping the extent of impacts on water. The global climate database of WorldClim is used as a reliable set of mean climatological conditions. Population density and distribution data are also of major importance for this analysis, including the presence of roads and location of urban areas, both as sites of human footprint and areas where water quality has an impact of human beneficiaries. As expected, the presence of mines, and oil and gas wells, together with the mapping of mining and oil and gas concessions are treated as a key dataset.

WaterWorld yields a series of hydrological relevant results, as part of its sophisticated analysis. For the purpose of this chapter, I focused on the water quality aspects and the significance that extractives pose on this water feature for the region of study. The variable examined is the human footprint on water quality (HF), which, as described above in section 5.2.1, is a compound hydrological metric of water quality. The HF index is used as a proxy for water quality, since it aggregates human influences on water and cumulates them downstream along the flow network. Essentially for each pixel in a hydrological drainage network the HF considers two main components: first, the flow from upstream precipitation on a human influenced land use that may contain point (mining, oil and gas, roads) or non-point (croplands, pastures, urban areas) potential sources of contamination; and second, the flow of water from precipitation on "natural land", which has no human land use or is protected and thus is assumed to have no human footprint. Considering these two components, for each cell the amount of water that fell as rain on upstream human land uses is combined with the total water available from all areas to that cell, and the ratio of this potentially contaminated contribution is calculated and expressed as a percentage of water in that cell that may be polluted. I focused on the extractives sources of potential contamination and their impact regionally and locally in relation to other sources. The baseline scenario establishes an initial point that includes all current human activities, even the existing mining sites and oil and gas wells. Based on this baseline, I designed the appropriate future scenarios of extractive development, and calculated the change between them.

5.2.5 PREPARING A SCENARIO OF FUTURE DEVELOPMENT

With the aim of analysing the significance of mining and oil and gas extractives development, this section explains how I designed scenarios for development of mining and oil and gas in the region. First of all, both extractives are modelled in different scenarios to better identify the extent of change of each extractive activity in the region.

MINING DEVELOPMENT SCENARIO

Mining concessions are considered first, starting with the calculation of a realistic development scenario, based on the preliminary observations described below from actual mining sites in the region. It is understood that the impact of mining activities in general varies depending on both the size of the area mined and, the type of mining technique to be used, the proximity to downstream populations and the local hydrological conditions amongst other factors. In order to generate realistic scenarios of what proportion of new concession areas might be mined I looked at existing concessions in areas where mining has developed over a number of decades and I calculated the area of mined pixels as a fraction of the area of the concession in order to set a maximum limit to the scenarios to operationalise in new concessions. Thus, for each mapped mining site one pixel is assigned, and then the number of sites (i.e. count of mining pixels) within a concession is divided by the total number of pixels (i.e. total count of pixels) that the concession covers. This was repeated for all mining sites and concessions for which data was available, and the average percentages then calculated.

The calculated mean percentage of use within a concession was determined at 5.5%, assuming that open-pit techniques are going to be applied and the specified percentage of land (i.e. the pixels in which the mines occur) will be completely altered. This assumption is based on the fact that a majority of the mining permits surveyed within the available data (3 of every 4, with coal deposits being the most prevalent in Colombia) are requested for minerals that are extracted as part of the superficial ore layers mined as opencast, hence effectively changing the land cover and land use to bare soil and mining, respectively.

As discussed previously, this analysis was done at two resolutions, hence the mining sites were also represented at both resolutions. Although it is understood that mining sites in reality are more complex than points, as it can be seen in some high resolution imagery with the pixels on both 1Km² (Figure 5-7*a*), and 1 Ha (Figure 5-7*b*) resolutions, that rasterising the data allows for sophisticated spatial modelling while maintaining an appropriate representation of the complexities of the real mining polygons. Figure 5-7 shows several mining sites mapped in the western surroundings of Medellin, Colombia. More complex representations of mined area forms will not be possible until a global or regional mining polygon dataset is produced.

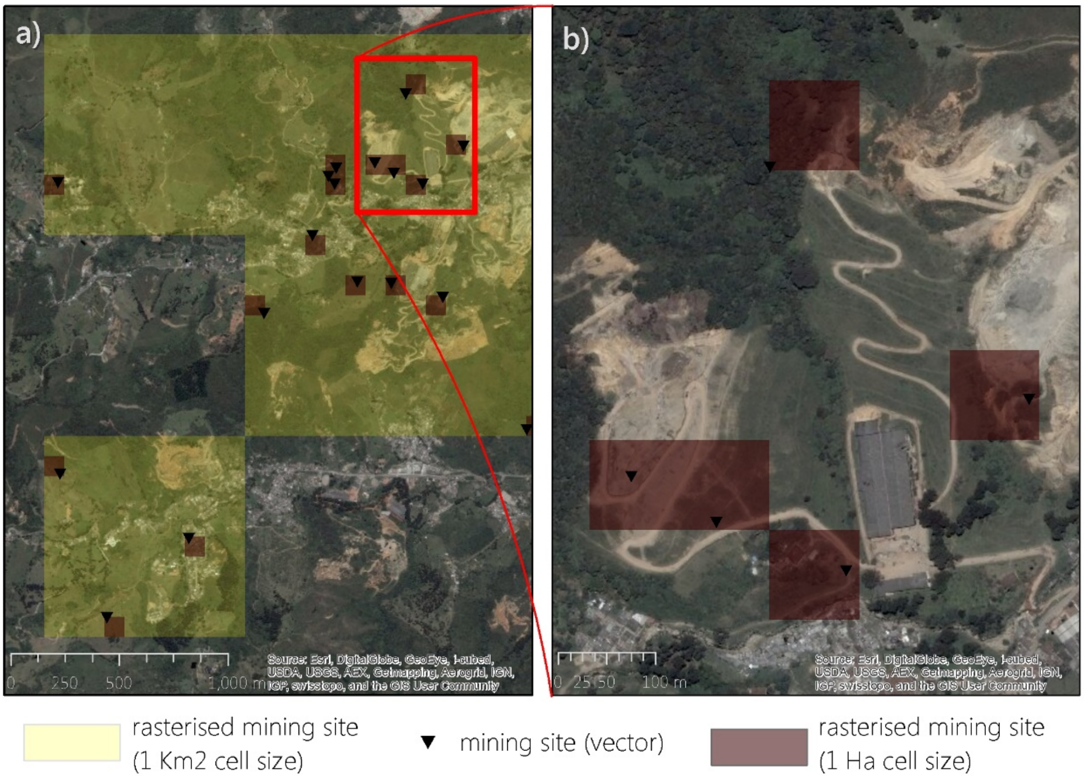

Figure 5-7 Mining sites mapped as vector points, and then rasterised at *a)* 1Km² resolution, and *b)* 1Ha cell size

OIL AND GAS CONCESSIONS DEVELOPMENT

The approach for oil and gas concessions followed a similar principle. First, all the mapped sites with a presence of oil and gas wells and infrastructure were included and rasterised. Furthermore, all the major pipelines, and major roads within the concessions were also counted as oil and gas sites and rasterised. This assumption was made since the main reason for the opening of those roads are precisely the extractive activities that take place in these, previously, remote and isolated areas (WWF, 2013) and they and their associated pipelines are certainly sites of potential contamination. Once all of the oil and gas infrastructure was added over the whole region of the Western Amazon and overlaid by concessions, an overall average was calculated using the count for oil and gas pixels relative to the whole concession raster (Figure 5-8). This preliminary result yielded a percentage of 1.22%. This fraction is a realistic number for the region, so it was used as the input percentage of change in the oil and gas scenarios, thus within the model that much land cover was changed to bare soil and the respective land use was turned into oil and gas extraction. The model takes these changes into account when calculating the variation of the output variable of water quality (HF).

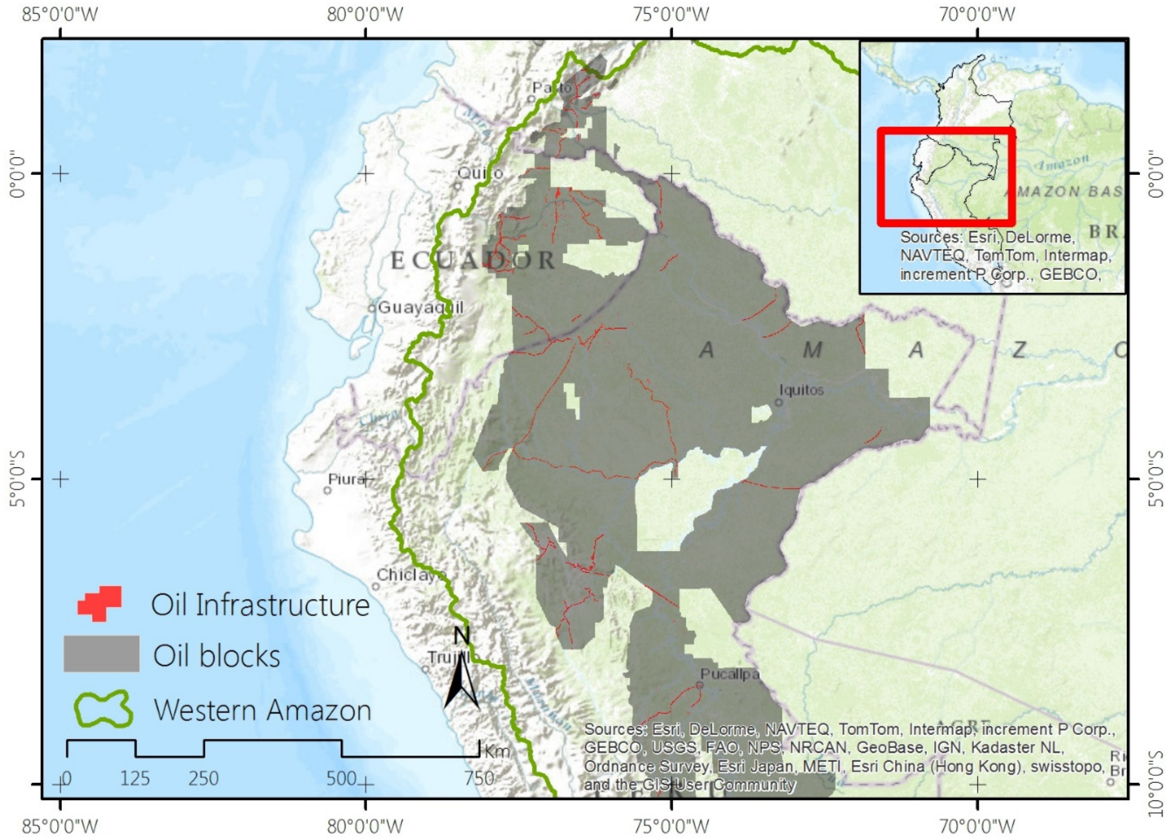

Figure 5-8 Oil and gas infrastructure within the boundaries of oil concessions in the Western Amazon

Scenarios within WaterWorld

Once the potential development percentage was calculated, and having the baseline already run, the scenarios can start to be developed within the WaterWorld tool. First, the land use and cover change (LUCC) model was set up by establishing a negative change of -100% of tree cover for the calculated 5.5% of the land where mining concessions are present. The LUCC model starts selecting the pixels that are more likely to be changed according to their proximity to roads, population and infrastructure, and then it allows for the clustering of pixels by a process of convolution (Figure 5-9*a*). The resulting layer of clustered pixels is then used to change land cover and use to represent extractives (Figure 5-9*b*).

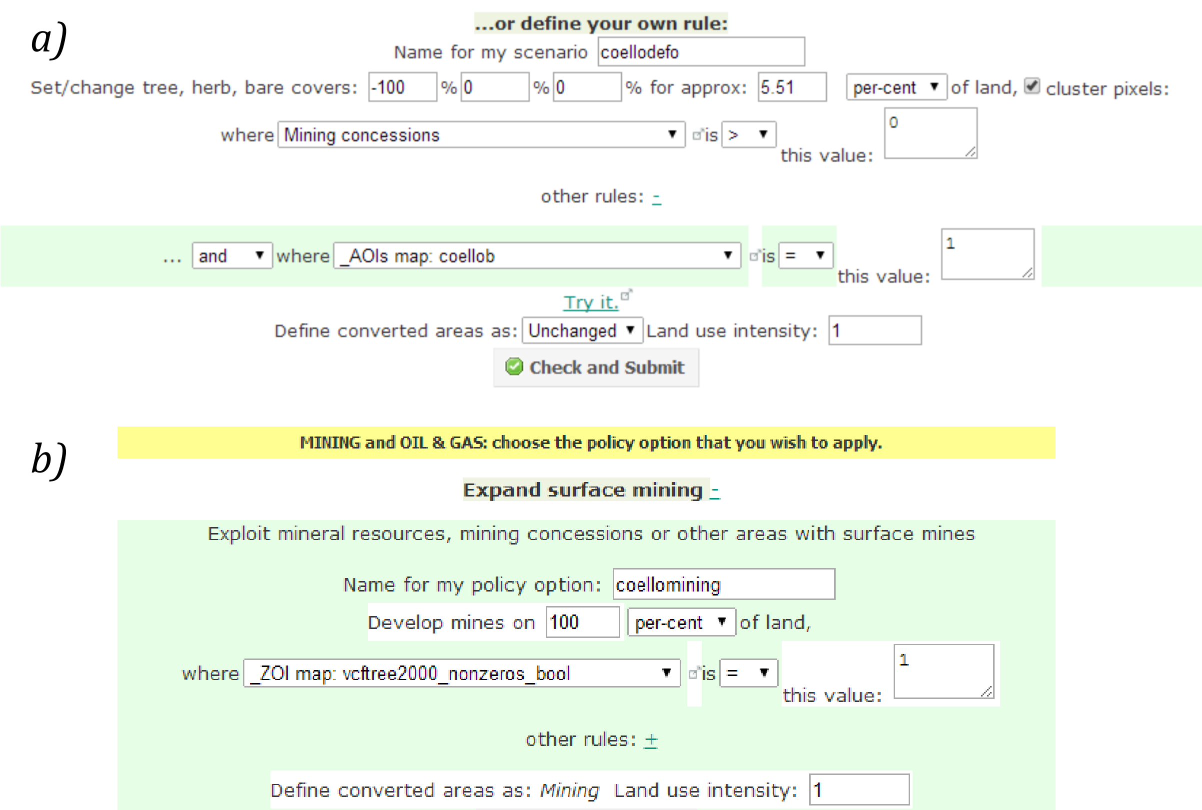

Figure 5-9 Setup of extractive scenarios within the WaterWorld policy support tool. The example shows the *a)* land cover change (LCC) model and the subsequent *b)* land use change (LUC) extractives scenario for surface mining

The same procedure was used to model the oil and gas development using both the LUCC model and then the extractives model for LUCC, and using the abovementioned 1.22% for the development of the oil and gas concessions.

Both mining and oil and gas scenarios were first run at 1 Km^2 resolution for the two tiles of the Andes and Western Amazon. The local tile for the Grand Coello only includes mining concessions, so this scenario was run at 1 Ha resolution. Similarly, the Tiputini tile was run for the oil & development scenario only at this focus area with 1 Ha resolution. In total, the analysis included eight runs covering the areas of Colombia and Ecuador (1 Km^2 resolution), and the

Grand Coello and Tiputini (1 Ha), and having a baseline for each, plus a mining scenario and an oil and gas scenario, where applicable (Table 5-2).

Table 5-2 Model runs in the WaterWorld policy support system covering the Andes and the Western Amazon, at the two operational resolutions.

Tile reference	Baseline	Mining	Oil and gas
Colombia	1 Km^2	1 Km^2	-
Ecuador	1 Km^2	-	1 Km^2
G. Coello	1 Ha	1 Ha	-
Tiputini	1 Ha	-	1 Ha

5.3 Results

The results are presented below going from general (i.e.regional) to specific (i.e. local) scales and details. Firstly, the baseline human footprint is evaluated for the Andes and Western Amazon regions, and then the focal areas of the Grand Coello and Tiputini Rivers. The development scenarios for Mining and Oil and gas are analysed at the same scales and detail.

5.3.1 The Baseline Human footprint on water quality

The baseline scenario was masked out to only present the mining and oil and gas concessions for a more relevant analysis of the current human footprint. Oppositely, the development scenarios extend to areas outside the concessions, since the impacts on water quality may flow downstream and reach areas outside these man-made boundaries.

5.3.1.1 Baseline Water Quality within Mining Concessions

The baseline HF calculated for the whole region was masked by the mining concessions, but the levels of potential contamination still vary across the full range 0 to 100%. In fact, there is a significant group of concessions in Zamora, South Ecuador currently not developed and located in remote and sparsely populated areas, showing very low HF (<5%, Figure 5-10*a*).

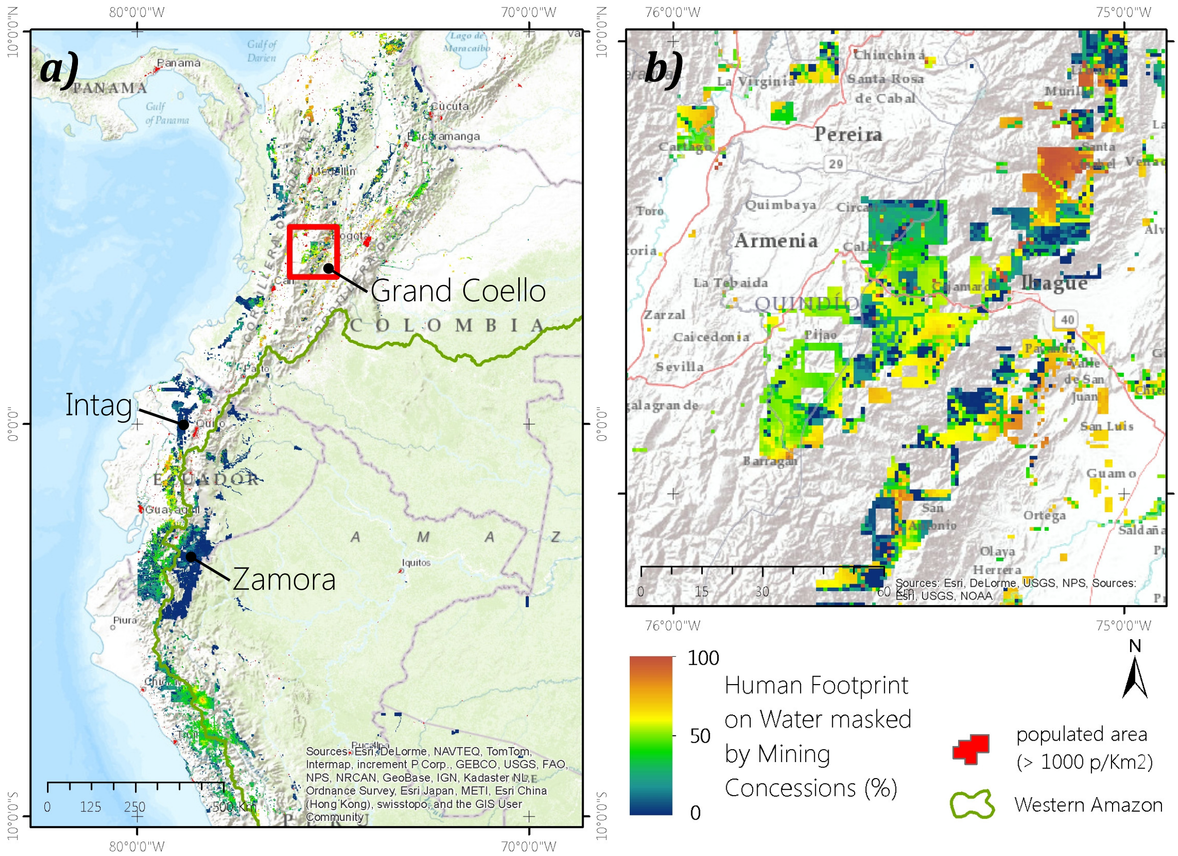

Figure 5-10 Human Footprint on Water Index (%), masked by the mining concessions for *a)* the Andes and Western Amazon within the region of study, and *b)* detail of the Grand Coello region, at 1Km² resolution

Those undeveloped concessions currently overlap with Shuar territory, although the newly formed state-owned mining company of Ecuador is pushing forward a potential mining development in the near future (Empresa Nacional Minera del Ecuador, 2013). A similar situation can be identified in the Andean region of Intag, Northern Ecuador, where several mining concessions are located, despite the local populations' persistent counterattacks to the mining development efforts (Bebbington et al., 2008). Furthermore, these concessions intersect with a protected area (i.e. Cotacachi Cayapas). The baseline HF is relatively low (<10%) in comparison with the rest of areas. Analysing the whole of Ecuador is a clear example on how the Andes are the main focus of current and future development of mining. The current impacts observed on water quality are attributed to the croplands and pastures in some extent, and presence of urban areas, roads and bare soil patches are also causing more punctual impacts. Sampling random points of interest in the HF result map masked by concessions yield an average of 60% of the HF coming from agricultural and grazing lands, whilst a minimum 2% was directly related to mining sites.

More than half (51%) of the Grand Coello region, west from the city of Ibague, is within a mining concession. However, the baseline HF shows other activities that are of significance. The main river channels that cumulate these impacts are not completely visible at this scale (Figure 5-10*b*), hence the need and additional contribution of a higher resolution analysis. In general, the pattern in Colombia is similar to Ecuador, where the mountainous Andes areas have a concentration of mining concessions, though other anthropogenic activities –croplands, pastures, urban areas, and roads – are currently driving the numbers of HF.

By definition, the HF index measures the impact of all human activities, and even though it weighs extractives higher than agricultural activities (a value of 1.0 compared with a fraction between 0 and 1 according to cover for croplands and pasture), the index represents the aggregation of all those activities coming from upstream to a point of measure. Hence, the average baseline HF for all the mining concessions is 23% (Table 5-3). Values of zero HF are included in the average as those pixels are assumed to be areas where all available water is free from human impact, though they only account for 10% of the concessions area. The population that would be directly impacted by the development of these concessions is approximately 4.3 million people.

Table 5-3 Statistics for the baseline human footprint and population density for the mining concessions in the Western Amazon.

Variable of interest	Min	Max	Sum	Count	Mean	Area Fraction
Mining Concessions HF (%)						
All	0	100	3,200,000	147,000	**23.0**	1.00
Zero	0	0	0	14,300	-	0.10
population density (persons/Km^2)						
Zero	0	0	0	14,300	-	**0.10**
Positives (MOI)	0	47000	**4,300,000**	132,000	33.5	0.91

5.3.1.2 Baseline Water Quality within Oil and gas Concessions

As described in the introductory section, the oil concessions cover a much more extensive area compared to the mining concessions. Overall, the ratio of oil and gas concessions to mining concession areas is 5:1, although the percentage of development within the concession is less on average, the absolute numbers (i.e. area affected) would be comparatively greater. Furthermore, the location of this development and their connection with the surrounding ecosystems is what is being analysed. The highest human footprint (HF>50%) is located on agricultural lands across the Andes. Nevertheless, a vast portion of the area of concessions within the lowlands of the Western Amazon have a very low current impact (HF<5%, Figure 5-11*a*).

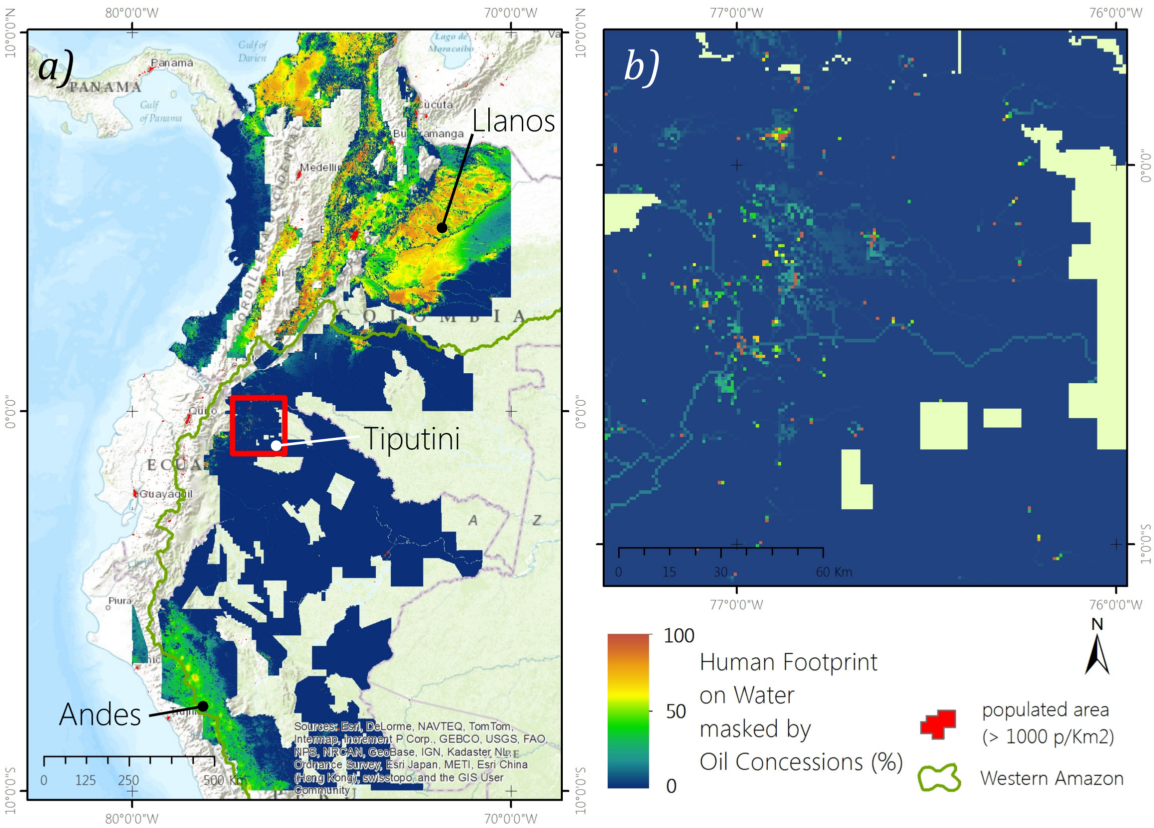

Figure 5-11 Human Footprint on Water Index (%), masked by the oil and gas concessions for *a)* the Andes and Western Amazon, and *b)* detail of the Tiputini River region, at 1Km² resolution

Looking in detail, Northeast Ecuador shows a distinctive pattern of point sources of potential contamination that are then diluted but still transported downstream (Figure 5-11*b*). As previously established, this region of the Tiputini River has a four-decade history of oil extraction. Thus, the pattern follows the location of oil and gas infrastructure that makes up part of the human footprint metric. Furthermore, the HF index capabilities allow to visualise the transport of this impact through the flow network hundreds of kilometres down the river, reaching outside the area of concession and consequently affecting other regions off-site, which in this case is the heart of Yasuni National Park. Clearly for different types of contaminant the safe exposure will differ such that agricultural nitrates may still be safe at a fraction of 1% but mining residues including cyanide may have safe limits much lower and this has to be factored in when examining the downstream decay in order to plot above which concentration footprints are still significant for human health or other impacts.

The current HF baseline shows high footprint (HF>50%) in the Llanos area in Northeastern Colombia, although it has minor human occupation and a savannah-like vegetation (WWF, 2014), it is extensively used for cattle ranching and other impacting activities on water quality. The Llanos are classified as herbaceous cover within the model, due to an average of 0.9 herb-cover fraction for that area, and a big portion of this is actual pasture land.

Overall, the oil and gas concessions are mostly located in lowlands, and a mean of 15.3% of HF was calculated (Table 5-4), which is comparatively lower than the mean for the mining concessions baseline. This is due to the extent of oil and gas concessions located in the Western Amazon, where there is relatively low extractive development and relatively low human occupation. In fact, a big portion (38%) of the area is classified as natural, showing an insignificant human footprint (HF=0%). Nevertheless, a total of 34 million people live within the areas of the concessions, which includes heavily populated cities in the Andes of Colombia. Even more, all the areas analysed are under some human pressure and being located within an oil and gas concession makes them highly susceptible to future threats where extractive development may be targeted.

Table 5-4 Statistics for the baseline human footprint and population density for the oil and gas concessions in the Western Amazon.

Variable of interest	Min	Max	Sum	Count	Mean	Area Fraction
Oil and Gas Concessions HF (%)						
All	0	100	19,500,000	1,210,000	**15.3**	1.00
Zero	0	0	0	450,000	-	0.38
population density (persons/Km^2)						
Zero	0	0	0	450,000	-	**0.38**
Positives	0	55000	**33,900,000**	770,000	38.0	0.62

5.3.1.3 Baseline Water Quality in the Grand Coello

The analysis at a higher resolution (pixel size = 1Ha) allows for better calculation, visualisation and understanding of the spatial variability and patterns in the baseline HF for the Grand Coello basin and its surrounding areas. Figure 5-12 shows the study area in the Central Colombian Andes, and highlights the regions within mining concessions. In the North, the presence of the Nevados National Park displays a pattern where HF=0 by definition (protected areas are a source of clean water downstream in the HF index calculation). Despite this, in the NW concessions, the baseline values are already high (HF>50%) due to the pasture and croplands present in the area.

Within the Grand Coello basin limits, the current human footprint is moderate (HF<50%), which again is due to croplands and pastures, despite being a mountainous region. The few populated places show localised high impact which is quickly diluted by surrounding lower impact inputs to the visible river channels. The city of Ibague falls in part inside the basin and its impact on water quality can be observed locally and downstream along the Combeima and Coello Rivers.

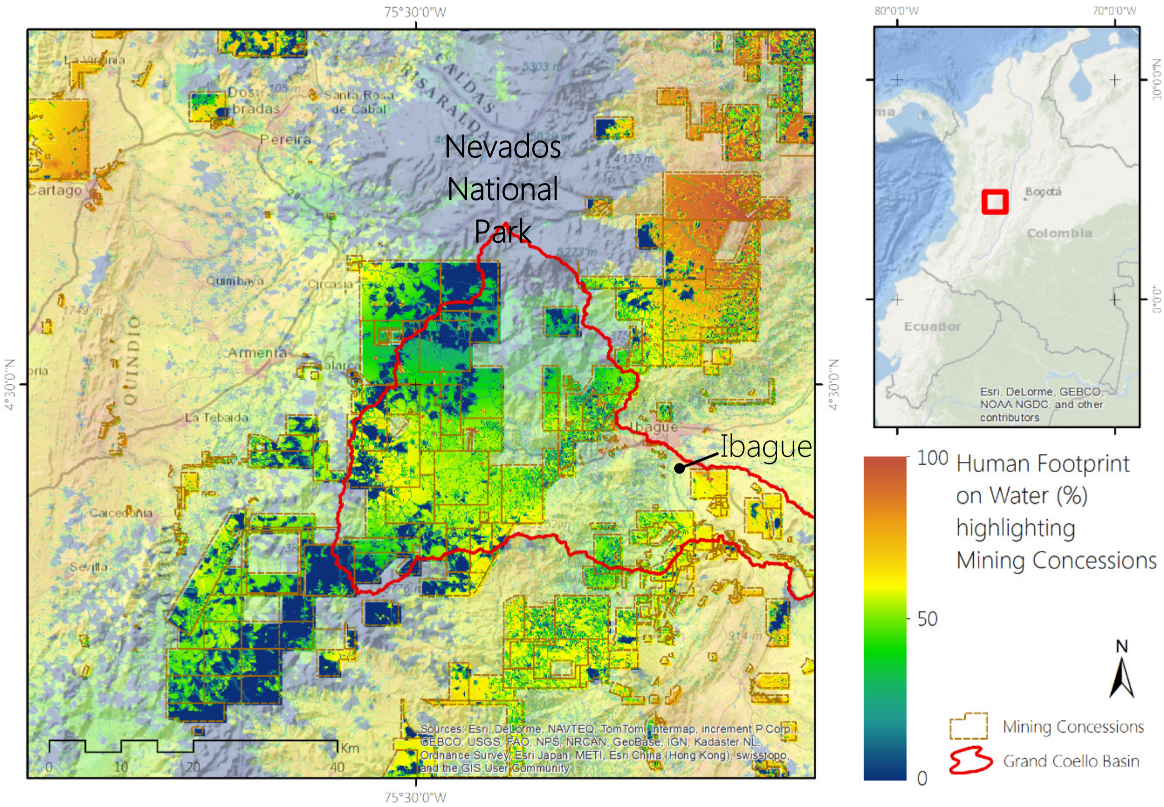

Figure 5-12 Human Footprint on Water quality Index (%), highlighting the mining concessions for the Grand Coello region in the Andes of Colombia, at 1Ha resolution

Overall, the mining concessions in the region have a baseline human footprint of 43% on average, with only 2% of the area currently free of any human impact (Table 5-5). An approximate 300,000 people currently inhabit the areas and would be directly affected by the potential mining developments. Even though the main focus is on extractives, it is important to identify all current pressures, in order to later identify the changes that mining development would cause.

Table 5-5 Statistics for the baseline human footprint and population density for the mining concessions in the Grand Coello region.

Variable of interest	Min	Max	Sum	Count	Mean	Area Fraction
Mining Concessions HF (%)						
All	0	100	15,000,000	360,000	**43.0**	1.00
Zero	0	0	0	8,600	-	0.02
population density (persons/Ha)						
Zero	0	0	0	8,600	-	**0.02**
Positives	0	350	**310,000**	360,000	1	0.98

5.3.1.4 Baseline Water Quality in the Tiputini

The situation for the Tiputini region contrasts with the findings for the Grand Coello. Average HF for the whole area under concession is only 1% (Table 5-6), which means current pressure is much localised in the oil and gas infrastructure. Even though only 17% of the area is completely free of human footprint, the total number of people directly affected by the baseline footprint is approximately 91,000 persons, who are mainly located in the NorthWest region of the tile of study, with two distinctive urban areas, Sacha and Shushufindi (Figure 5-13).

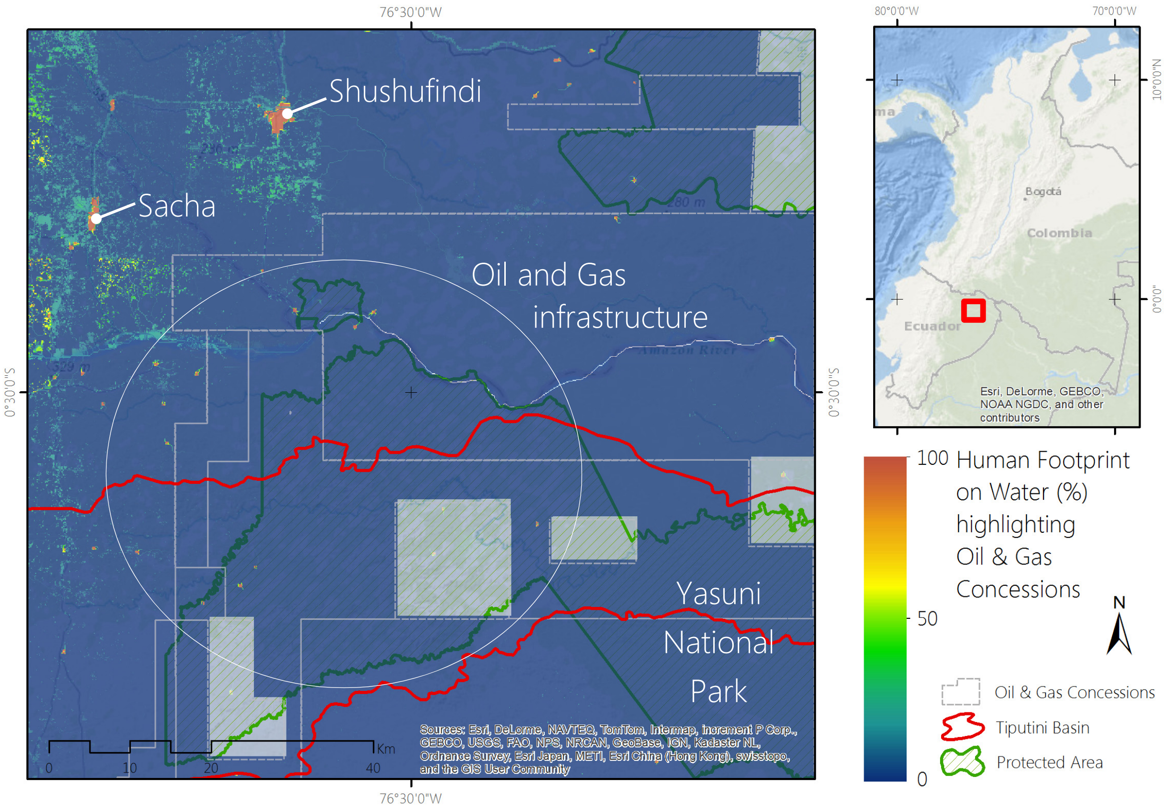

Figure 5-13 Human Footprint on Water Index (%), masked by the oil and gas concessions for the Tiputini region in the Amazon of Ecuador, at 1Ha resolution

Furthermore, the road infrastructure and relatively small pasture and cropland areas have a locally relevant impact (HF>50%). In the rest of the oil and gas concessions, there are several points of localised HF impact due to the presence of oil infrastructure. The Tiputini River basin goes across the south part of the tile and has very low HF (<5%).

Table 5-6 Statistics for the baseline human footprint and population density for the oil and gas concessions in the Tiputini region.

Areas	Min	Max	Sum	Count	Mean	Area Fraction
Oil and gas concessions HF (%)						
All	0	100	1400000	1300000	**1.0**	1.00
Zero	0	0	0	220000	-	0.17
population density (persons/Ha)						
Zero	0	0	0	220,000	-	**0.17**
Positives	0	97	**91,000**	1,100,000	0	0.83

Nevertheless, the few point sources of potential contamination are spread around the concessions and are of serious concern because they overlap with the Yasuni National Park. This has been recognised throughout this whole study as an area of paramount importance due to its uniquely high biodiversity (Bass et al., 2010), high potential ecosystem services, and currently increasing political significance nationally and worldwide (Puig, 2013; Rival, 2014).

The baseline components have been established and analysed, so now the development scenarios are presented, and the significance of the extractive industries on water quality is discussed both at regional and local scale.

5.3.2 Scenario of Mining Development and its Impacts on Water Quality

The mining development of 5.5% of the concessions led to several noteworthy changes. Resulting data were analysed at two levels, and at the two cell-size resolutions. The analysis for mining was done for the Colombia tile at 1Km^2, and the change (Δ) between the development scenario and the baseline scenario is averaged by major sub-basin in Figure 5-14. The changes at the sub-basin scale are relatively small, only reaching around 2%. The major impact is localised in the pixels where mining development was modelled, thus HF reaches 100% in almost 800 pixels (8 Km^2 of land), as seen in the histogram of the data (Figure 5-15).

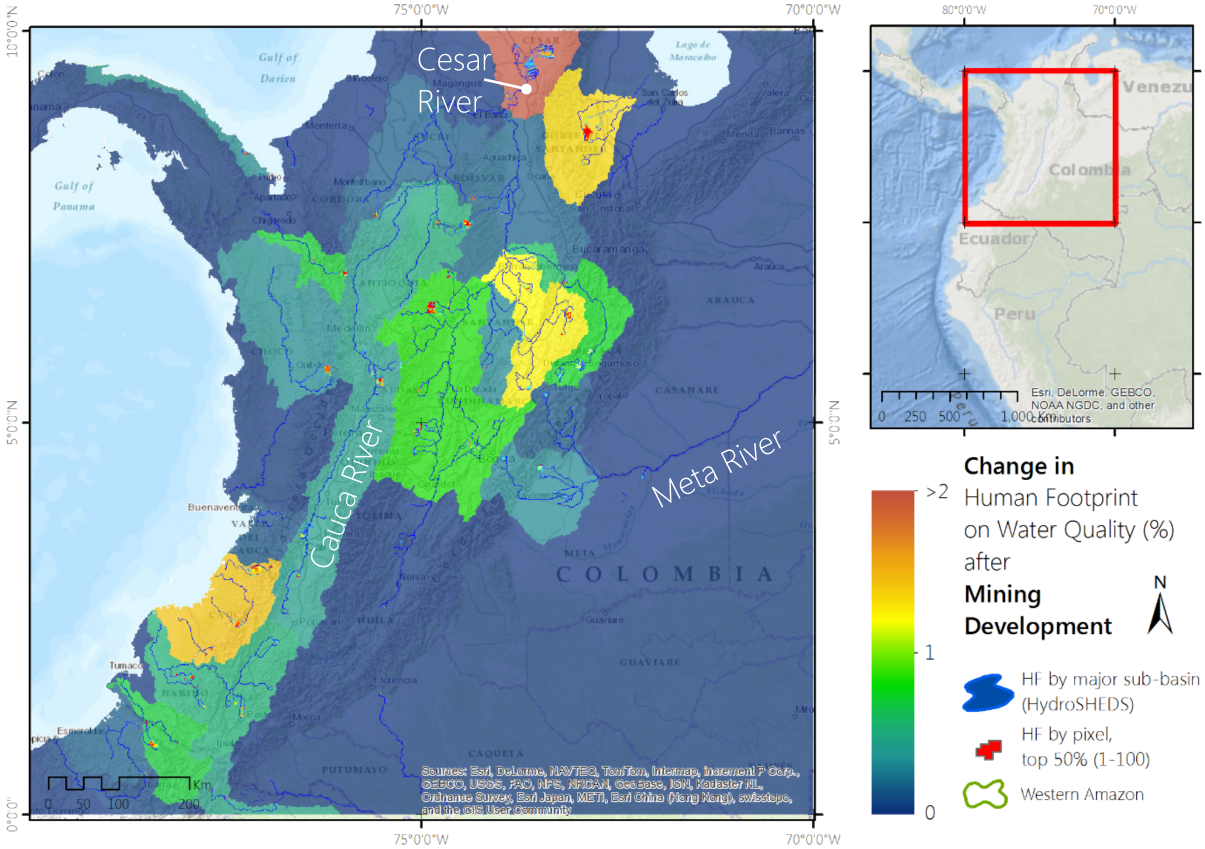

Figure 5-14 Change in Human Footprint on Water quality Index summarised by major sub-basin, overlaying the top 50% pixel-based change in HF, at 1Km² resolution

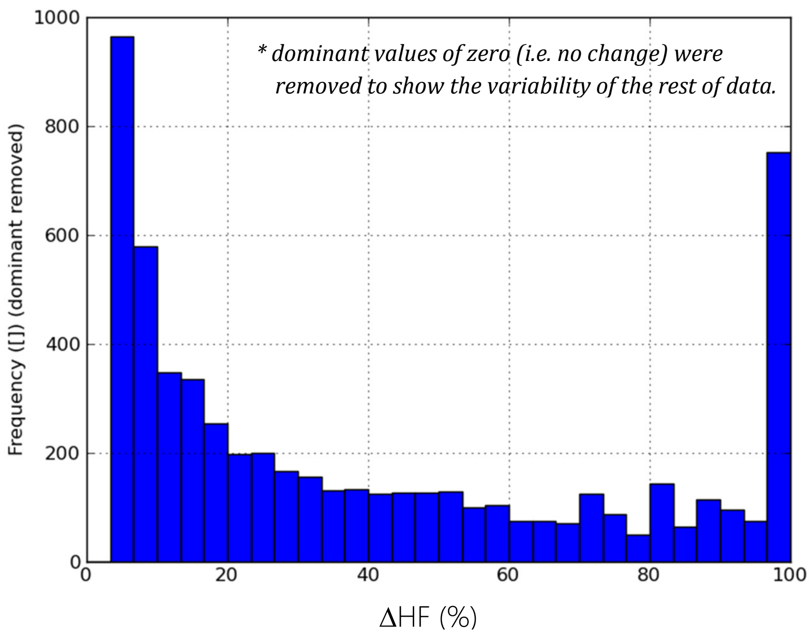

Figure 5-15 Frequency distribution of Change in Human Footprint on Water Index by pixel under a mining development scenario

More importantly, these impacts are transported through the flow network, and even though they are diluted with the runoff coming from other areas, they can potentially reach hundreds or thousands of kilometres downstream. For example the potential mining development in the upper catchment of the Cauca River, in the south of country could develop contaminants that can travel along the whole of the river way northwards to the Atlantic Ocean. Furthermore, the contribution of several mining development areas is all collected downstream and reaches the maximum modelled change of +2% HF (Table 5-7) over the Cesar River (shown in reddish-brown in Figure 5-14). The Andes topography in general is a conduit for the potential human footprint derived by the extractive development. Even more, the impacts of relatively small developments in the centre of the country may potentially affect the whole region of the Llanos in the eastern part of the country contaminating the waters of the Meta River, which crosses the international boundary and reaches the floodplains of Venezuela.

Table 5-7 Summary of statistics for the Human Footprint Index and population density in the mining concessions development modelled scenario in the Andes of Colombia.

Variable of interest	Min	Max	Sum	Count	Mean	Area Fraction
Change in Human footprint on water (ΔHF %)						
Complete tile	0	**2**	250,000	1,100,000	**0.22**	1
Zero	0	0	0	500,000	-	0.44
Positives	>0	2	250,000	**640,000**	**0.39**	0.56
population density (persons/Km2)						
Positives (MOI)	0	65,000	**39,000,000**	640,000	61	0.56

The changes on far distances in the river network are all below 0.5%, which at first glance can seem insignificant. However, considering that mining tailings can contain cyanide, the maximum level for drinking water, established by studies of the Environmental Protection Agency of the United States, is 0.2 mg/L or 200 ppb, parts per billion, (Environmental Protection Agency, 2013). That is a percentage of 0.000000002%, which places these figures of human footprint from mining activities in a completely different perspective. Clearly, the mining industry takes actions to minimise its impacts, but if an accident occurs, as they have in several places (Rico et al., 2008), then the consequences are inevitable. In the extreme case scenario that all the modelled mining sites contaminate the influenced waterways, the total number of people that would be affected sums to 39 million people (Table 5-7), which is approximately 80% of the total population of Colombia.

5.3.2.1 CHANGES IN THE HUMAN FOOTPRINT OF THE GRAND COELLO BASIN

The results at this higher resolution are summarised by sub-catchments. The observed changes display higher detail but they follow similar patterns when compared to the lower resolution modelling. In the case of the Grand Coello, the upper sub-catchments on the west part of the basin yielded higher rates of change than the lower catchments (Figure 5-16).

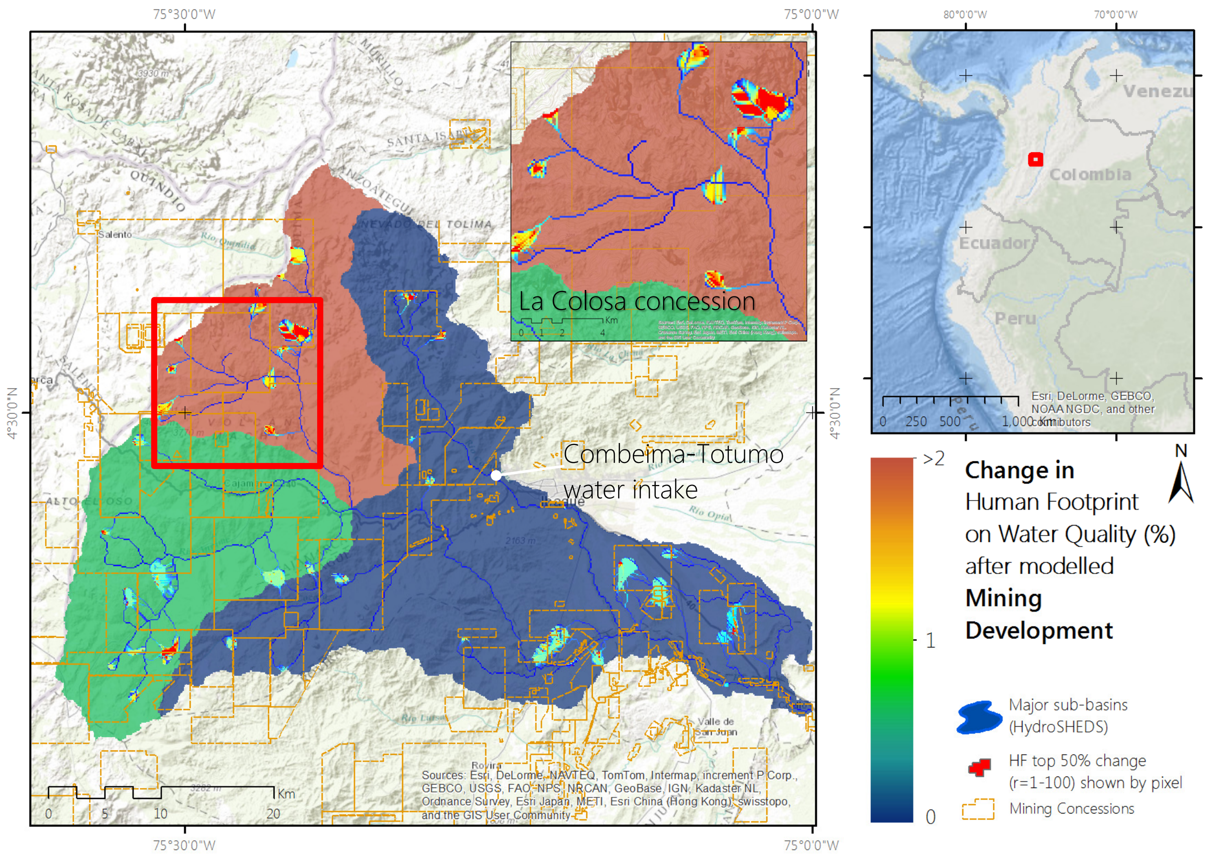

Figure 5-16 Change in Human Footprint on Water Index summarised by sub-catchment, overlaying the top 50% pixel-based change in HF, at 1Ha resolution, in the Grand Coello Basin

All major changes occur within the areas of the concessions, reaching localised values of 100% in HF change. This high impact is rapidly diluted, though it is still perceptible downstream. Nevertheless this small change can be of relevance when it comes to mining residues. For instance, when looking at the water intake point for the city of Ibague (Combeima-Totumo, 4.44N, -75.24W), the baseline HF was 24.5%, and it went up, after the extractive development, to 25.2%. This 0.7% can cause significant impacts on the water provision for the city where toxic contaminants are concerned. These impacts in turn may cause increased efforts and costs to provide drinking water, and ultimately means there is less water available for other uses, such as human consumption and agriculture.

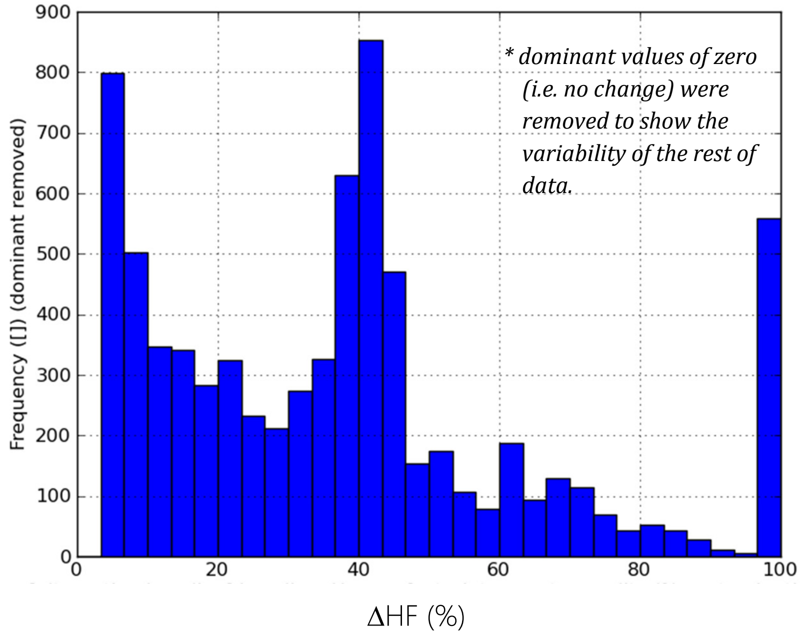

Figure 5-17 Frequency distribution of Change in Human Footprint on Water Index by pixel for the Coello region under a mining development scenario

The average change in HF is only 1.5%, though high changes can be found in localised areas of direct impact. These maximum changes are localised in 500 cells (5 Km2) where ΔHF=100%. The frequency distribution (Figure 5-17) shows the pixel change variation across the board, and medium changes (ΔHF~40%) are found in the micro basins of the mountainous regions of the upper Coello. There are approximately 340,000 people locally and downstream that would be affected by these developments (Table 5-8). Furthermore, the impacts of these developments would easily escape the boundaries of the concession, unless appropriate mitigation measures are taken, and potentially contaminate the water that is currently used by the local inhabitants downstream. Several iterations of the model, changing the percentages of development, can inform to the extent of the potential impacts and the existence of thresholds for impact, but it also can contribute to a better planning of land and water management, and a more informed decision making process.

Table 5-8 Summary of statistics for changes in modelled Human Footprint Index, and population density in the Grand Coello Basin.

Areas	Min	Max	Sum	Count	Mean	Area Fraction
Change in Human footprint on water (ΔHF %)						
Basin (only positives)	1.1	2.5	290,000	190,000	**1.5**	1.00
Mining concessions	1.1	2.5	170,000	110,000	1.5	**0.55**
population density (persons/Ha)						
Positives	0	480	**340,000**	190,000	2	1.00

5.3.3 Scenario of Oil and gas Development and its impacts on Water Quality

The oil and gas scenario of development for the Western Amazon in Ecuador and Peru results in an extensive change along all the sub-basins. The model shows changes up to 2% on a major sub-basin basis, spread over vast areas of catchment that could potentially lead to significant human and ecological impacts. More than 60% of the area is impacted at some level (HF>0%, Table 5-9), with a minimum set change of 1.22% of direct impact by the oil activities (i.e. cells converted to oil and gas infrastructure). This shows how intricate, connected and delicate a river network system is. Figure 5-18 highlights in reddish-brown the basins with major changes due to the modelled development. The first, in the north of Peru is the Corrientes River, which currently has several oil extraction activities present, hence the model assigns further development in the neighbouring pixels. These changes are carried downstream to its confluence with the Tigre River, and then the Marañon even further downstream. The other relevant basin with ΔHF>2% is the Ucayali in the centre of the Peruvian Amazon, which includes a good part of the Pacaya-Samiria protected area, currently covered with rainforest and partially overlapped by the oil concessions, which makes it susceptible to be impacted by the extractive development.

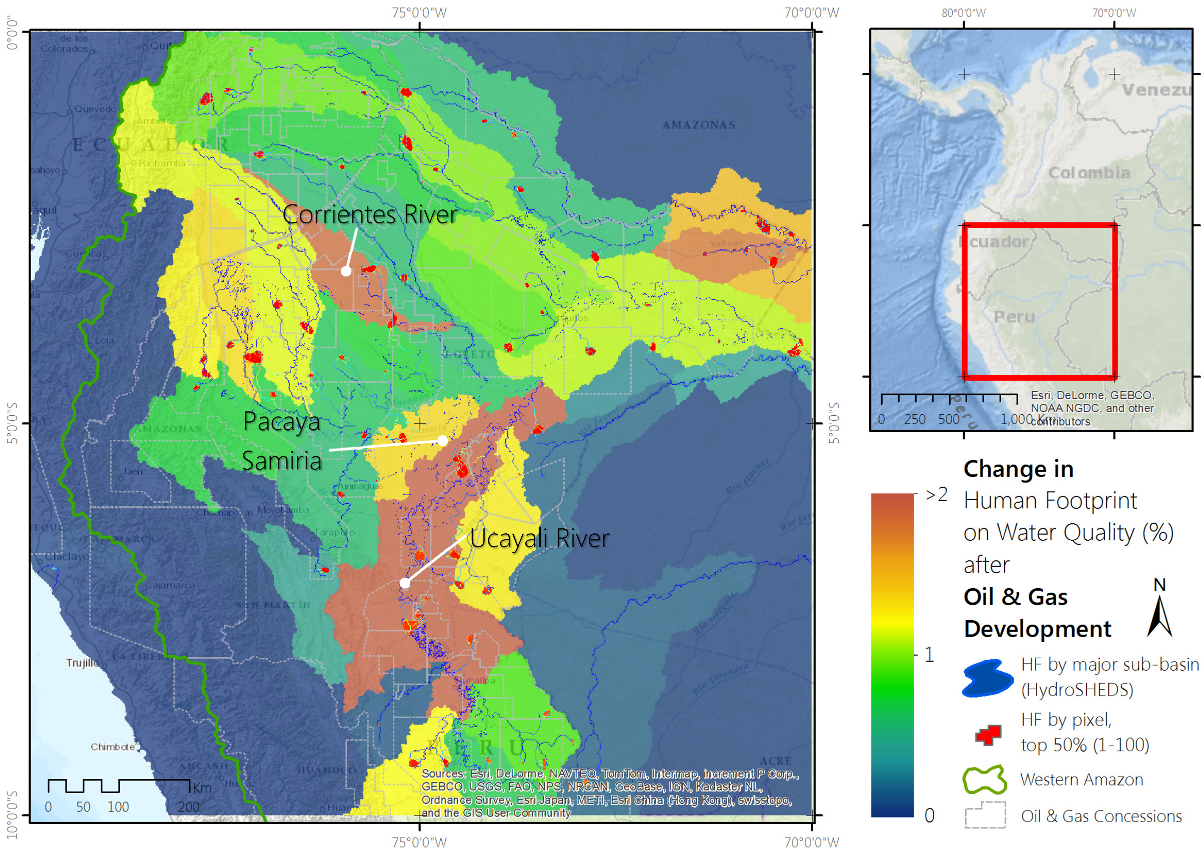

Figure 5-18 Modelled Change in Human Footprint on Water Index summarised by major sub-basin, overlaying the top 50% pixel-based change in HF, at 1Km² resolution

The model assigns several development areas and these have high localised changes (ΔHF=100%), that together sum to ~5,000 Km² according to the frequency distribution of the data analysed (Figure 5-19). The analysis of a comprehensive network of oil infrastructure was already done in the multi-criteria approach of Chapter 3, but it lacked the consideration of the oil development impacts flowing downstream the rivers. In reality, most of the Environmental Impact Assessments (EIAs) presented for environmental approval to the authorities and agencies for extraction activities do not include this important consideration. The potential impacts of the activity travel far down the flow network, and could certainly cross international boundaries. For instance, the contamination of Ecuador's water could potentially reach

Peruvian territory. Furthermore, these impacts can accumulate with the extraction impacts in Peru and reach as far as the Brazilian Amazon. This is relevant both as chronic and acute contamination of oil and gas residues has proven to be harmful and long-lasting (Kimerling, 1991; San Sebastian and Hurtig, 2005). Firstly, the model was run for one average year, whilst the potential contamination would accumulate over many years, even if it is at very small levels, in water courses and the food chain potentially creating chronic and long-lasting pollution. Secondly, in the case of an accident with high levels of contamination, the impacts will rapidly reach the lower parts of the catchment. An oil spill occurred in May 2013, releasing a volume between 7,000 to 11,000 barrels of oil to the water flow of the Napo River in Ecuador. The oil slick reached the Peruvian Amazon in a couple of days and it was expected to reach Brazil in less than 10 days after the spill accident (HOY, 2013). Modelling tools, like WaterWorld, can help understand and thus develop policy and management options to minimise the impacts in the case of these unfortunate accidents.

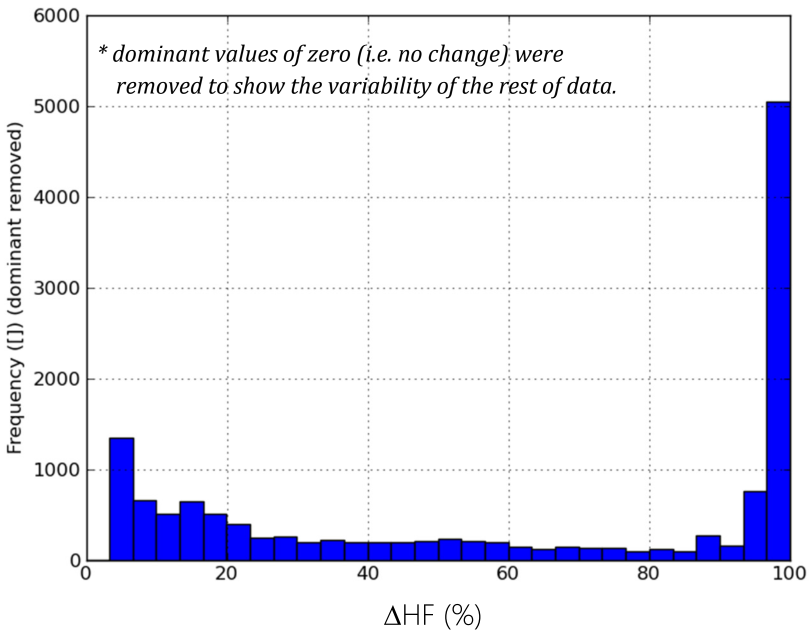

Figure 5-19 Frequency distribution of Change in Human Footprint on Water Index by pixel for the Western Amazon region under oil and gas development scenario

Even though, the calculated value for the area of development was smaller for oil and gas concessions (1.22%) than the mining concessions (5.5%), if the absolute numbers of the changed area are analysed (Tables 5-9 and 5-7) the total area affected by oil and gas, ~840,000Km^2 , surpasses the area that mining concessions would affect, ~640,000Km^2. This is due to the area of the concessions for oil and gas, which were calculated to be, on average, 6 times larger than an average mining concession in the region. Finally, it was calculated that 4.7 million people would be directly affected by the changes in water quality modelled for the oil and gas concessions development (Table 5-9)

Table 5-9 Summary of statistics for Human Footprint Index and population density for modelled oil and gas concessions development in the Western Amazon.

Variable of interest	Min	Max	Sum	Count	Mean	Area Fraction
Change in Human footprint on water (ΔHF %)						
All basins	0	2.3	840,000	1,400,000	0.61	1
Oil and gas concessions	0	2.3	480,000	560,000	0.86	0.4
population density (persons/Km2)						
Positives	0	49,000	**4,700,000**	860,000	5.5	0.62

5.3.3.1 Changes in Human Footprint of the Tiputini Basin

The Tiputini catchment was chosen due to its complex combination of high potential ecosystems services provision, elevated biodiversity, high conservation importance, and even an untouchable reserve for a voluntarily-isolated group of indigenous people contrasting with an overlay of numerous oil and gas concessions (Figure 5-20). The potential development of this area of Ecuador should be handled with delicate care, and modelling potential scenarios before taking any further actions is a recommendable approach. Using the established 1.22% of development within the concessions, the results in Table 5-10 show that a minimal fraction of the area is directly affected (0.2%). The area that is develop by the model accounts for 3,400 Ha (34 Km^2), which in turn end up affecting a total area of approximately 16,000 Ha (160 Km^2).

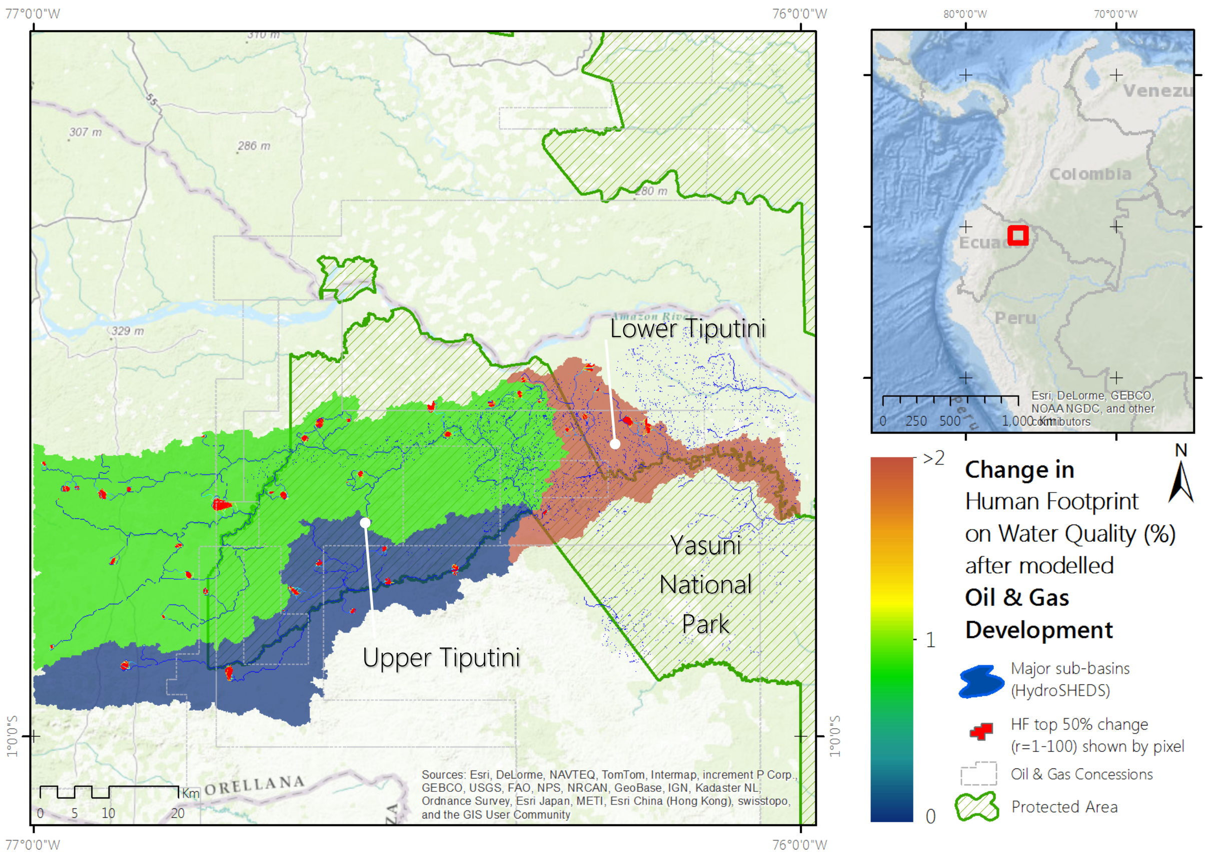

Figure 5-20 Change in Human Footprint on Water Index summarised by sub-catchment, overlaying the top 50% pixel-based change and its contribution of HF to the runoff, at 1 Ha resolution, for the oil and gas scenario within the Tiputini Basin

The spatial pattern of the developments and the statistics are within the expected values of change for a typical oil and gas development. The lower catchment of the Tiputini suffers the highest change since it collects the impacts from the developments upstream. As previously discussed, the contamination caused in one exploitation site could travel hundreds of kilometres downstream and affect areas that are supposedly under strict conservation. That is the case of several zones of the Yasuni National Park, which by definition should be free of any extractive activity. The park is currently overlapped and has oil and gas infrastructure built inside the park, operated by the spanish company Repsol-YPF, and it will have, in the near future, further extractive activities occurring in the eastern concessions already assigned to the ecuadorian company PetroAmazonas (Pappalardo et al., 2013). Further research and improvement of these modelling tools and scenarios development can help to design a better location and routing systems for the future developments.

The areas of modelled direct impact are spread in small clusters around the rainforest, which would cause irreversible damage due to the increased edge effect that these clusters will have on species richness and biodiversity (Laurance, 2008). Furthermore, the mean ΔHF for those areas of change is very high at 89%. This large change is due to fact that the baseline HF in almost all the basin started at a very low level (HF~0%). Hence, the pixels of change will be highly localised in the developed areas and easily reach a change of 100%, as it can be seen in the histogram in Figure 5-21, where the highest changes reach a pixel count equivalent to 2,500 Ha (2,5 Km^2). The impact flows in lesser extent than in the mining scenario due to the flat topography of the Amazon, when compared to the mountainous Andes.

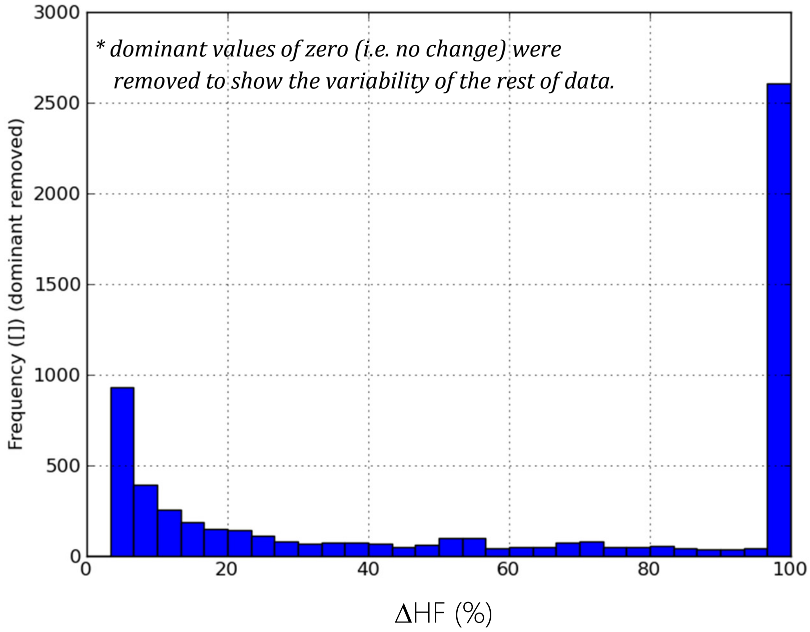

Figure 5-21 Frequency distribution of Change in Human Footprint on Water Index by pixel for the Tiputini Basin under an oil and gas development scenario

The number of people living in the area and directly affected by modelled activities is calculated to be 550 since there are no big settlements in the region (Table 5-10). These number may seem low compared to the previous analysis on mining scenarios. However, the few people that live in these territories are indigenous people, Kichwa and Waorani, and a group of the latter, the Tagaeri, who live in voluntary isolation. The respect and preservation of their culture has been recognised of world-wide importance by the UNESCO and confirmed via Presidential Decree by the government of Ecuador (Pappalardo et al., 2013). Consequently, these relatively low numbers represent much more when they are set in the correct context.

Table 5-10 Summary of statistics for Human Footprint Index Statistics and population density for the modelled scenario of development of oil and gas concessions in the Tiputini River

Areas	Min	Max	Sum	Count	Mean	Area Fraction
Change in Human footprint on water (ΔHF %)						
Basin	-1.3	100	360,000	1,400,000	0.25	1.00
Positives	0	100	360,000	15,000	24	0.01
Oil & gas developments	0.19	100	300,000	3,400	**89**	**0.002**
population density (persons/Ha)						
Positives	0	10	**550**	16,000	0	0.01

5.3.4 VALIDATION WITH OBSERVED DATA

The Management and Ordinance Plan for the Grand Coello Basin, POMCA, included a baseline study on water quality on more than 30 locations in different points of the basin (Cortolima, 2005). These sampling points in the report are not properly geo-referenced, so with the help of a local NGO expert (Rubiano, 2014), a subset of the points were geo-referenced to fit both the named location, and the cell-based local direction drainage network used by WaterWorld. These locations have an observed measurement for the Water Quality General Index, IGCA (Indice General de Calidad del Agua), which was derived from the Water Quality Index, WQI, originally designed for small rivers in the United States, and applied in several local basins (Miller et al., 1986). The IGCA, similarly to the HF, is a dimensionless number, from 1 to 100, that combines different quality factors measured in the field, and weighed them accordingly to represent the water quality in a sample location, being 100 the optimal quality for water. In turn, the human footprint index measures the impact of human activities from 1 to 100. Since they both are indices, then the inverse function (i.e. 1-IGCA) can be used to compared, and potentially validate the modelled water quality information. Thus, the baseline HF derived from WaterWorld was queried for the same sample locations (Table 5-11).

Table 5-11 Sample points for water quality in the Grand Coello Basin, showing the WaterWorld baseline human footprint (HF), the POMCA Water Quality General Index (IGCA), and the altitude of the sampling point in metres above sea level (masl), and its normalised value (alt_N) by which the data were organised.

Sample point	HF (%)	IGCA dimensionless	1–IGCA dimensionless	difference	altitude (masl)	alt_N
Rio Anaime Paramo	4.4	81.1	18.9	14.5	3533	100
Quebrada Campoalegre	11.3	68.7	31.3	20.0	2073	59
Rio Toche	11.3	68.1	31.9	20.6	2073	59
Quebrada Carrizales	32.7	66.1	33.9	1.2	2052	58
Rio Cocora Dantas	43.5	64.5	35.5	-8.0	2043	58
Quebrada Las Perlas	16.8	62.6	37.4	20.6	1950	55
Rio Bermellon Los Alpes	39.9	64.4	35.6	-4.3	1820	52
Rio Anaime	35.5	64.7	35.3	-0.2	1778	50
Q. Cay Sector alto	44.8	63.2	36.8	-8.0	1611	46
R. Bermellon San Lorenzo	37.8	63.1	36.9	-0.9	1600	45
Rio Coello Penaranda	30.3	58.8	41.2	10.9	1388	39
Q. Cay Sector bajo	24.0	61.9	38.1	14.1	1300	37
Rio Cocora	43.1	63.2	36.8	-6.3	1275	36
Rio Combeima Totumo	24.6	43.0	57.0	32.4	1200	34
Rio Coello Cocora	42.7	57.3	42.7	0.0	1145	32
Quebrada Andes	43.4	64.6	35.4	-8.0	850	24
Rio Coello Caracolito	69.8	55.0	45.0	-24.8	576	16
Quebrada La Barbona	34.9	52.9	47.1	12.2	479	14
Quebrada Potrerilla	59.2	58.9	41.1	-18.1	460	13

The results were plotted and a linear regression was calculated (Figure 5-22), showing a weak correlation between the data (Pearson = 0.43; R^2 = 0.1876). Nevertheless the pattern of both indices can be observed to match in most of the locations. With the premise that upstream water in this type of mountainous basins would be expected to be less impacted, the data were organised by altitude. When plotting the data, including the normalised altitude (alt_N), the upper sample point in the *paramo* region is very low, as expected, for both indices (Figure 5-23).

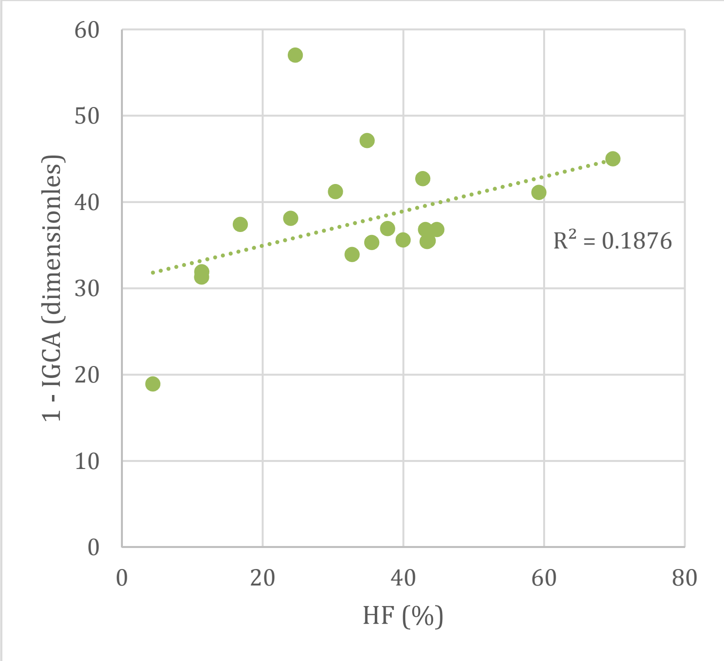

Figure 5-22 Human Footprint on Water plotted against the inverse function of the Water Quality General Index for the Grand Coello region

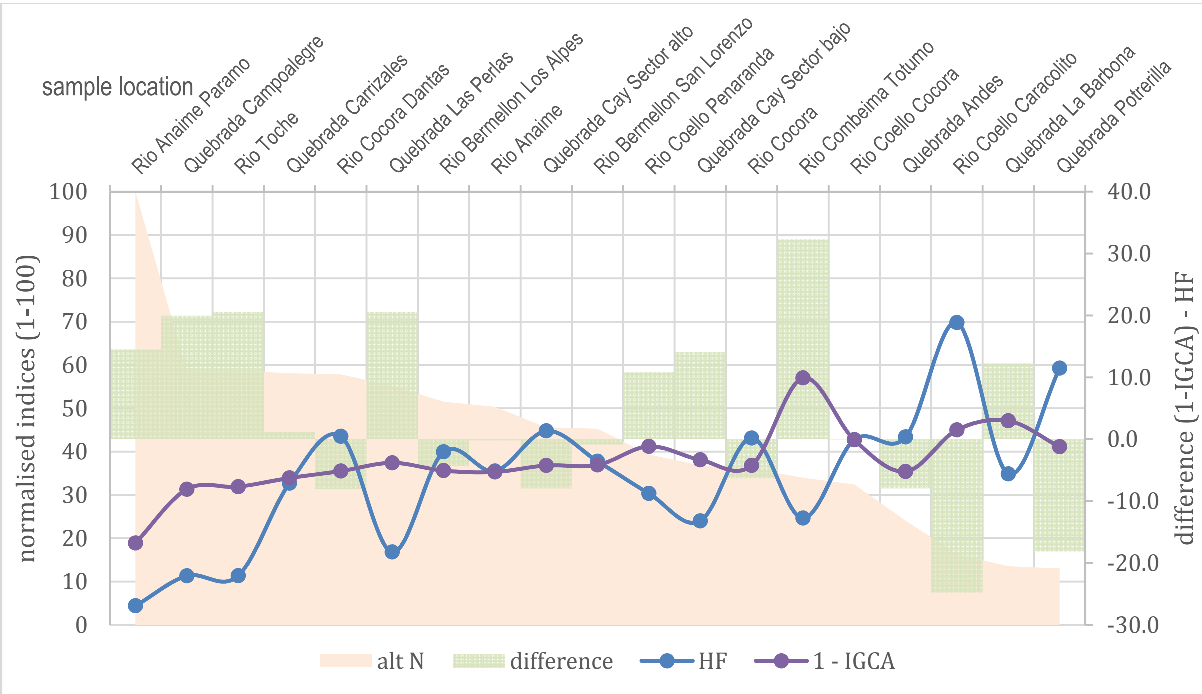

Figure 5-23 Validation of Human Footprint on Water Index using the Water Quality General Index for observed locations in the Grand Coello Region. Data are plotted in altitude order. The normalised altitude of the sample locations is shown in the background for reference

The differences are less significant in the mid ranges, and the indices coincide in four out of nineteen sampling points (22%). The highest difference is located in the water intake point for the city of Ibague (Rio Combeima Totumo), showing a higher-than-average value for the inverse IGCA and a lower-than-average value for HF. In any case, the tendency of upstream points having better water quality than downstream points can be observed. One of the caveats of this analysis is that populated places are not taken into account, though they do have influence on water quality.

5.3.5 UNCERTAINTY CONSIDERATIONS

The WaterWorld model is not calibrated to a specific location, which makes it feasible to apply it in any type of environment, but there is uncertainty in the results that the model yields. The analysis of the differences between observed data and modelled results was used to evaluate this uncertainty (Table 5-12). Considering that both indices have a range of 0 to 100, a mean difference of 3.57 in their measures is acceptable. However, the standard deviation of 14.77 increases the uncertainty. The confidence level at 95.0% of the measurements is 7.12, which means than 95% of modelled value would have an error of just about 7 points in the scale. Overall, the main components of a complex hydrological system are taken into account, but there are minor and random events that cannot be included or measured. Even though the model accuracy of prediction has some level of uncertainty, the visualisation of change in space and its patterns are valid, and this study tested this innovative measure of human footprint on water. Consequently, it can be said that the HF index is a valid and consistent parameter to use as a proxy for water quality in spatial modelling.

Table 5-12 Uncertainty analysis of the difference between HF and IGCA indices.

Statistical measure	value	Statistical measure	value
Mean	3.5668	Minimum	-24.774
Standard Error	3.3873	Maximum	32.355
Median	-0.0425	Sum	67.769
Standard Deviation	14.7652	Count	19
Range	57.13	Confidence Level (95.0%)	7.11662

5.4 CONCLUSIONS

The model application was successful on showing the expected results in terms of the significance of mining, and oil and gas developments on water quality. The modelling tool was put to test and provided relevant information in all the proposed setups: the baseline run and the scenarios of development, using the two working scales of regional and local scope, and considering topographically opposite regions as the Andes and Western Amazon, where the mining and oil and gas extraction activities take place. The following points are the key findings of the analysis and conclusions derived from the results:

- The baseline scenario is the starting point that supports the modelled scenarios, and the human footprint on water demonstrated to resemble correctly the expected patterns of current human influence. The water quality of the Andes is already impacted by various anthropogenic activities, amongst which mining sites represent a localised impact. However, deeper analysis and extreme care should be placed into planning and evaluating new mining developments, especially with large-scale mining projects that are expected to have large and long-lasting impacts (Specht, 2013). Baseline measures in remote places inside undeveloped mining concessions have low human footprint. These areas are particularly susceptible to changes on water quality when development comes into the picture, and having low population densities makes them more susceptible to be targeted for development.

- The water quality of the lowlands in the Western Amazon is on average lowly impacted by human activities. However, the few localised sources of pollution are directly connected to oil and gas infrastructure in the region, and the same baseline results show how this human footprint impairs water quality much further downstream following the flow network and reaching outside the concessions. This consideration should be included in the Environmental Impact Assessments that are required to be presented by the oil and gas companies and Environmental Strategic Assessments that drive environmental policy.

- Working at different scales allows for a variety of observations to be detected at the regional and local levels. The wider resolution portrays the big picture and allows to recognise spatial patterns that are repeated and connected within a region, such as a typical layout of oil wells and oil roads within a concession, and their connected impact on the river ways. The results at finer resolution allow to observe the main and minor river channels that transport and diffuse the human impacts, and how they can reach areas of local significance that would be averaged out at the larger resolution.

- The scenario setup chose realistic changes in terms of area for the proposed developments. The detected changes are localised in the few pixels of modelled development, resembling the observations of real extractive activities. Since the only change introduced are the extractive activities, the measured results show exclusively their impacts significance and extent. It is understood that the impacts will be minimised in the case of a real development, where all environmental regulations would be followed to avoid the impacts. However, the model helps to visualise and understand how straightforward it is for contaminants to flow downstream. Furthermore, the model runs for one average year, hence it does not account for the accumulation of toxics that can potentially build up over the decades of time that extractive concessions normally last.

- Within the scenario deployment, it is also unstated that other human activities, such as agriculture, will occur concurrently to the extractive developments. They will also have an influence, as it was observed in the baseline runs in the Andes. Modelling the concurrent changes would yield more realistic results, but it would fail on pinpointing the direct cause of the measured changes.

- Within the countries of study, particularly in the area of Madre de Dios in Peru, a significant portion of mining extraction is implemented at artisanal and small scale (Ashe, 2012; Adler Miserendino et al., 2013). Most of this artisanal mining sites are not properly regulated, hence they are not listed in the official concession inventories (Telmer and Veiga, 2009), so it is difficult to determine their extent and impact. Furthermore, primitive techniques used in these sites lack safety and security measures, thus making them more likely to produce contaminants. The discussion on why these groups of artisanal miners prefer, or are compelled, to use outdated techniques goes beyond the scope of this study. Nonetheless, the prospective application of these modelling tools is precisely to support planning processes and environmental policy making and enforcement by the regulatory authorities and agencies, in co-participation with other stakeholders.

- The current analysis does not, nor does it attempt to, provide all the answers for a flawless development of the extractives, but it can deliver several pointers towards that direction. The pixels that the model targets for development are selected based on the established rules to resemble a realistic extractive pattern, but it is not a planning tool to be used by extractive companies. In the case of oil and gas developments, the changes normally show a pattern of linear infrastructure (i.e. roads, pipelines) connecting point site of extraction (i.e. wells, pumping stations), which were more difficult to resemble in the model. However, newer versions of the model will precisely take into account recommendations of the current application, in order to improve its results. Additionally, the WaterWorld model accounts for water-dissolved impacts, whilst crude oil interacts in a completely different way and does not mix with water. Once in contact with water, crude oil will create a millimetric layer of oil that spreads on the surface since it is less dense than water (Larrea, 2009). This slick layer is the major concern on a real oil spillage and further development of the modelling tool can help to portray this pattern and contribute towards a more realistic and oil-specific set of results.

- Ultimately, this research can contribute with spatial data and scientific information to the stakeholders' interactions; it can certainly contribute towards an informed process of decision making, and in due course to policy making and enforcement, as it was effectively achieved in the Grand Coello basin through the Citizen Action Negotation process (Candelo et al. 2014). The potential of these modelling tools to support an informed decision making process is substantial, as they can be further develop towards the specific needs of the stakeholders facing the extractive-development scenarios that the Andes and Western Amazon will potentially experience in the coming years.

CHAPTER 6

CONCLUSIONS, RECOMMENDATIONS AND FURTHER WORK

6.1 OVERVIEW

This research as a whole provided insight into current and potential future environmental impacts of extractive industries in the Western Amazon and the Andes regions within Colombia, Ecuador and Peru. In this concluding chapter, the aim and objectives of the thesis are revisited in light of the work done. Furthermore, this section summarises and connects the substantive arguments of each of the three empirical chapters, and reflect on the contribution of this thesis to existing research. Finally, recognising the limitations inherent to research, there is space for recommendations of future work and the implications of the results for the research community and for policy makers.

I start by emphasising here that this research did not seek universal answers –which are difficult to come by in complex problems like this– but rather to contribute substantially towards a more geographical, spatial, numerate and scientific approach to the evaluation of the extractive industries impacts for the regions of the Andes and Western Amazon. The use of advanced GIS techniques and sophisticated spatial modelling tools allows for a more geographically comprehensive approach that goes beyond the single intervention focus of EIAs and SEAs and the case study-based approach of previous literature (Bjureby, 2006; Tarras-Wahlberg et al., 2001; Warnaars, 2012). This approach integrates multiple ecosystem services, biodiversity metrics, and multiple threats in a single work space to inform and suggest solutions on conservation prioritisation issues.

6.2 MAIN FINDINGS

In order to summarise the main findings of this study, I start by revisiting the objectives specified in section 1.4, which were fulfilled in the empirical chapters and contributed to solve the stated research problem. The following main conclusions connected to each chapter were drawn:

- Chapter 3: Historic and current impacts of oil and gas extraction mapped in the Western Amazon put at risk the ecosystem services provision in the region. Similar studies have shown the overlap of oil and gas concessions with protected areas and indigenous territories with implication on biodiversity (Finer et al., 2008) and socio political conflicts (Orta Martinez et al., 2007). The contribution of this study was to include considerations of ecosystem services that although connected to the conservation of biodiversity were not considered before in the area. Going beyond the overlay and intersect of datasets, this novel approach yielded a geo-visualisation of both ecosystem services and extractives pressure in a common spatial bivariate plot.

- Chapter 4: Conservation priorities must be defined with considerations of ecosystem services, biodiversity, current pressure and future threats. The inclusion of multiple considerations with a singular aim of conservation yielded a comprehensive set of topmost priority areas that include all the mentioned concerns at once. Global approaches have contributed by highlighting the risks posed by extractives on biodiversity (Butt et al., 2013) and mapping global ecosystem services (Naidoo et al., 2008); but they have lacked resolution and proper context at the regional scale of the Western Amazon. This study proposes the topmost priority areas for conservation in the region, and recognises they are partially included in the current protected areas system, but additional efforts should be directed to find compromises between the imminent extractive development by the local governments, and the recognition of the importance locally and globally of preserving these areas in the long term. Recommendation for 'best practices' in the oil and gas sector have been studied and proposed in the oil-rich region of Loreto, Peru (Finer et al., 2013). The results found for conservation priorities of this thesis can contribute to the research field of best practices by including the ecosystem services mapping techniques that they lack.

- Chapter 5: Extractive development would significantly impair the water quality of the Andes and Western Amazon. The extent and magnitude vary across the region according to the model outputs. Baseline scenario results displayed the considerable contribution to this impairment of water quality by other, non-extractive human activities. Agriculture in the Andes, as well as urbanised areas leave a trace on the water trail. However, modelled extractive development yielded a new set of considerations. Mining operations in the Andes would cause comparatively lesser impact extent in area, but highly localised impacts that could potentially harm the means of subsistence of local populations. On the other hand, modelled oil and gas extraction in the lowlands of the Amazon is larger in extent, though because of its isolation may cause harm to relatively less people. Nevertheless, the pristine rainforests that would be affected, hold immense value of globally- (e.g. carbon) and locally-relevant (e.g. water provision) ecosystem services and constitute the habitat of unique high levels of biodiversity. Extractives residues are known to be harmful and long-lasting pollutants of water sources (CSC, 2013; Kimerling, 1991; San Sebastian and Hurtig, 2005; Specht, 2014). Water management options should include a proper understanding of a simple basin approach by which it is considered that all the interventions that occur within the basin will have a local effect there and, despite their natural decay, will also have an impact downstream. This logical train of thought is difficult to communicate into decision and policy making processes, so the geo-visualisation of modelling tools helps by informing and clarifying the revealed upstream-downstream relationship logic.

6.3 Further Implications

The results of this thesis have further implications for two major areas: *a)* for the research community in the fields of mapping ecosystem services and conservation; and *b)* for the policy makers involved in extractive development within the Western Amazon.

6.3.1. Implications for the research community

- Modelling tools that map ecosystem services have caveats and limitations that need to be considered and worked upon. The theory, datasets, and analyses needed to further develop these models is a call to the research community working with ecosystem services mapping to continue developing these kind of tools. The contribution of more than two decades of work since the first global approaches were carried out to value ecosystem services and to consider the importance of natural capital (Costanza et al., 1998) has produced in turn more adequate approaches with better data and higher resolution (Naidoo et al., 2013). This study tested and applied a novel modelling tool, which is a contribution to this research field. However, Co$ting Nature's approach needs further work in terms of including all relevant datasets, and minimising uncertainty as the other similar tools do, before the scientific community agrees on a method to systematically identify areas of global importance for ecosystem services (Juffe-Bignoli et al., 2014)

- Various approaches on conservation prioritisation have been established at global extent by remarkable efforts based on biodiversity conservation, although with some overlap between them (Brooks et al., 2006; Myers et al., 2000); and increasingly more comprehensive and higher-resolution datasets are becoming available for several taxonomic groups (Naidoo et al., 2013). Similarly, the risks posed by oil and gas operations on biodiversity and protected areas have been evaluated at global (Butt et al., 2013), continental (Osti et al., 2011), and regional scales (Finer et al., 2008). This study is of contribution to the conservation community by establishing an inclusive approach that identifies sites of simultaneous conservation of biodiversity and preservation of ecosystem services provision, which can be used to reevaluate the current conservation priorities and, if necessary, to propose new ones. Such a comprehensive approach may help confirming that conserving critical sites for biodiversity can provide significant benefits to humanity (Larsen et al., 2012), and it may also lend a hand to allocate optimally the increasingly scarce conservation funds (Wilson et al., 2006).

6.3.2. Implications for policy makers

- Protected areas are the foundation of global conservation efforts, and policy makers working within the environmental agencies and ministries are responsible to effectively preserve them and propose the creation of new areas. The most current assessment of global protected area coverage reports an encouraging 15.4% of land and in-land waters sheltered by protected areas worldwide (Juffe-Bignoli et al., 2014). The conservation priorities found through the modelling approach in this study contribute to the work of conservation policy makers in two ways: *a)* it helps strengthening the case to protect the found priority sites already included in the current protected areas system; and *b)* it provides scientific and objective information to consider sites identified as priorities for proposing the creation of new protected areas. Thus, contributing towards meeting the Aichi targets to effectively protect 17% of the land, considering the importance of ecosystem services and biodiversity conservation.

- Policy makers involved in extractive development should demand from the industry to follow management options that factor in the presence of biodiversity and ecosystem services relevant sites within their assigned concessions. The modelled scenarios produced in this study can assist policy makers to establish these management options in a spatially explicit and consistent manner. Initiatives from the civil society are already supporting this process such as the voluntary environmental standards for oil and gas extractives proposed by Equitable Origin (2014), or the Sustainable Loreto for 2021 report (Dourojeanni 2011), which promote the use of spatial analysis tools to support their cases for a sustainable and equitable development. The areas of topmost priority for conservation found in this study, such as the Pacaya Samiria National Reserve in Peru, should be legally branded as no-go zones for extractives. This is a difficult but crucial task for policy makers, and society, to weigh biodiversity and ecosystem services' long term benefits over short term revenues from extraction in these priority sites. Ultimately, this thesis assists country governments, policy makers, and civil society to become more informed about the likely impacts of their extractive policies and practices on the ecosystem services we all rely on.

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APPENDICES

APPENDIX A

This appendix presents two additional case studies relevant to the historical impacts of 'extractives' in the Western Amazon, which are similar and complementary to those presented in Section 2.9

THE SARAYAKU VICTORY

In a similar way, the social conflicts that arose from the oil and gas exploration in Sarayaku territory (Southeastern Ecuador) during 2002 led, after a decade of litigation, to a ruling from the Inter-American Court of Human Rights in favour of the Sarayaku community in 2012, entitling them to a compensation from the Ecuadorian government and ceasing the exploratory activities. Despite this, the impacts of the exploratory wells and explosive material left in the forest are still present (Temper, 2012). Moreover, the potential threat of future development is never far, considering the new national constitution (enacted in 2008) that allows for voiding prior consultation and informed consent when a project is considered of national interest, with the decision then left solely to the President elect. This 'loophole' in the Ecuadorian Constitution allowed for the XI oil round bid in late 2013, by which the Ecuadorian government is calling for bids to international companies on the 21 new oil concessions in Southeastern Ecuador, over a 3,000 Km^2 area, which overlaps several indigenous territories (Pachamama, 2012, de la Cruz, 2005).

THE SHUAR STRUGGLE

Yet another example is the Shuar territory in Southeastern Ecuador, which has seen several conflicts from the early 1990s due to the mining concessions granted to international companies by the Ministry of Energy and Mines, which ignored the overlap of concessions with the traditional Shuar territory (Latorre, 2014). Several confrontations have taken place between the mining companies, the authorities and an organised majority of indigenous communities, part of the Interprovincial Federation of Shuar Centres, whom have fought, in some cases literally, to avoid the ingress of mining companies to their territory (Bjureby, 2006).

Similarly to the indigenous groups, the rural and peasant communities have also showed a strong resistance in certain locations where mining concessions have been granted by the central government without prior consultation, and thus conflicts have arisen. Rural communities in the Intag region, Ecuador managed to stop exploration activities altogether by means of strong protests, which led to the expulsion of the Canadian company Ascendant and a complete halt to their proposed activities (Bebbington et al., 2008).

APPENDIX B

The published paper titled 'Multicriteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon', which constitutes Chapter 3, is presented here as published in the International Journal of Geoinformatics, Vol.9, No.2, June 2013

Multi-Criteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon

Multi-Criteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon 45-52

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Abstract
Oil extraction operations can be found in all types of environment, including the most threatened and delicate tropical rainforests. The Western Amazon has been widely recognised for its biodiversity and important ecosystem services, but it is also rich in oil reserves. The governments of Colombia, Ecuador and Peru have been increasingly developing and exploiting oil resources in these remote areas and this exploitation is an important contribution to their national economies. This analysis aims to inform a more sustainable development of extractives in the region using innovative techniques of geo-visualisation. The results yield a comprehensive oil impact assessment for the region and then highlight environmentally important zones to finally visualise areas of significant environmental risk based on future planned oil developments. The maps show that areas most affected by oil activities, such as the Yasuni National Park, in Ecuador and the Corrientes River Basin, in Peru are also the source of ecosystem services and furthermore areas as the Manu National Park, in Peru, are in risk of losing their ecosystem services value due to oil development expected in the near future. A better understanding of the situation supported by scientific information and innovative geo-visualisation will help to put in place and enforce policies and thus minimise the socio-environmental impacts of the activity while maintaining the production of oil and associated revenue that is vital for the region's economy.

1. Introduction

Oil exploration in Ecuador, Peru and Colombia started in the early 1900s in the Gulf of Guayaquil Ecuador, the area of Talara in the northern coast of Peru and the Magdalena River Basin in Colombia (Hanratty, 1991 and Hudson, 1992). The oil industry is capable of generating significant revenues especially at times of high demand but it equally needs considerable investment, especially when working in isolated and remote areas (Ramos and Veiga, 2011). The infrastructure and activities required for oil exploitation traditionally include roads, wells, pipeline installations and construction of large production facilities (Baynard, 2011). The impacts of all these infrastructures are of great concern when they are built in delicate and important areas for conservation and the provision of ecosystem services. The national oil company in Colombia, Ecopetrol is in control of a large pipeline system that covers a significant part of the centre and north of the country and in minor extent in the southern border (Ecopetrol, 2010). In Ecuador, the Trans Ecuadorian Pipeline, SOTE and the OCP and Heavy Oil Pipeline are the main oil infrastructures that carry oil across the Andes (Mirabik, 1991 and Lucero, 1997). The oil and gas industries in Peru have constructed two major pipelines to extract resources from the Amazon all the way to the Pacific Coast for export and internal supply (Perupetro, 2010). There are several development projects, some already underway, that aim to expand the extraction of resources particularly towards less-explored areas in the Amazon (Presidency of Ecuador, 2012). On the other hand, the Western Amazon has been widely recognised for its high species richness and endemism. In fact, 20% of the Western Amazon territories are under some type of protection due to the encompassed biodiversity. Even more, there are more than a thousand indigenous territories (Bass et al., 2010, RAISG, 2009, Finer et al., 2008 and Lucero, 1997). One of the major impacts of oil contamination is on water resources. It is estimated as part of the Texaco lawsuit in Ecuador that it would cost some USD 27 billion to clean-up the polluted groundwater in the affected region (Amazon Watch, 2009). Furthermore, local people in the whole Western Amazon depend on sources of clean water that come from riverbeds and groundwater sources, as well as rainfall water collection particularly in the areas where oil pollution has been significant (UNICEF, 2009). The provision of ecosystem services has been recognised as a priority in the oil-impacted areas (Ojeda et al., 2008 and Bastian et al., in press) thus scientific information would help to better maintain their supply. The aim of this study is to provide information for a more sustainable development of extractives in the Western Amazon by highlighting the ecosystem service impacts of oil developments and using innovative GIS techniques to visualise and understand the risks and propose an optimal extraction and distribution strategies with lower socio-environmental impacts. To achieve this aim, firstly the construction of a comprehensive geographic database with all variables involved was set as an objective. On a second stage, the development of new techniques of geo-visualisation is set as a target in order to better represent and analyse focus areas.

2. Methods

The Western Amazon comprises areas of Colombia, Ecuador, Peru, Bolivia, Venezuela and Brazil. Geographically, our study area lies within the coordinates of latitude 10°N to 20°S, and 80°W to 60°W of longitude. Even though the GIS was developed and applied over the whole area, the focus of the analysis is on the Amazon of Colombia, Ecuador and Peru, due to similarities in both the ecosystem services and history of oil industry in these countries (Finer et al., 2008). An extensive research on publicly available data was completed. Data from official and governmental sources were combined with publicly available data from private (i.e. oil companies) and civil (i.e. NGOs) sectors, in order to build a comprehensive geographic database. The collected datasets include data for oil blocks, pipelines, wells, waste pits, stations, flares, as well as roads, local communities and river networks. Additional information on environmental variables (elevation, water balance, land cover, local drainage direction and watersheds) as well as social variables (administrative boundaries, urban areas, land use) was derived and merged from the SimTerra database (Mulligan, 2010a). Data research and gathering was exhaustive to assure that all the used variables cover the entire focus area. The pioneering way to compile all the available information into a consistent geographic database was achieved by keeping a simple raster format, obtained with the Inverse Distance Weighing deterministic method for multivariate interpolation (ESRI, 2011) maintaining a constant resolution, and built-in rules with the purpose of ease of update when additional data are included. Only when data was available for the whole focus area was it included in the analysis to maintain consistency in the weighting and results. More detailed information on the datasets included in the analysis is presented in Table 1.

Table 1: List of variables used for the GIS multi-criteria analysis of the oil activities impacts and ecosystems services provision in the Western Amazon

variable	source of information	data type	Units
Oil pipelines	(PETROECUADOR, 2010, ECOPETROL, 2010, PERUPETRO, 2010, EquitableOrigin, 2011and UNIGIS, 2010)	polyline	Km
Oil wells*	(UNIGIS, 2010 and ANH, 2012)	point	
Block - concessions	(Jenkins, 2009, ANH, 2012 and IBC, 2009)	polygon	Km^2
Elevation	(Farr and Kobrick, 2000)	raster	m(a.s.l)
Roads	(FAO-GIEWS, 2008)	raster	pixels
Urban areas	(CIESIN et al., 2004)	raster	classes
Amphibians spp. Richness	(Mulligan, 2010a using (IUCN et al., 2008b)	raster	# spp.
Birds spp. richness	(Mulligan, 2010a)	raster	# spp.
Mammals spp. Richness	(Mulligan, 2010a using (IUCN et al., 2008a)	raster	# spp.
Reptiles spp. Richness	(Mulligan, 2010a using (IUCN, 2010)	raster	# spp.
Protected Areas	(UNEP-WCMC, 2009)	raster	unique ID
Tree coverage	(Hansen et al., 2006)	raster	fraction
Carbon Stock	(Ruesch and Gibbs, 2008)	raster	tonnes/Km^2
Local water balance	(Hijmans et al., 2005 and Mulligan and Rubiano, 2010)	raster	mm/year

* in Colombia the mapped wells are currently not in exploitation within the area of study

Thus all data were pre-processed and when necessary rasterised to match a common resolution of 1 km per pixel. ArcGIS (v.10.0; ESRI, 2011), PCRaster (v.Nov.2009 and Utrecht University, 2009) and R (v.2.15.2; R, 2008) software packages were used for data management, geo-visualisation and analysis. Due to the large range of factors that determine the impact of oil activities in terrestrial environments, the most effective method to analyse variables of diverse units is a multi-criteria analysis (Boroushaki and Malczewski, 2010). First, a comprehensive analysis of the current oil infrastructure was performed with all the relevant variables to determine the extent of the oil impact in an index. Second, biological and physical variables were combined to determine an ecosystem services index by examination of the potential (i.e. provided but not necessarily used) ecosystem services (Mulligan et al., 2010). These services are calculated locally for every cell of analysis. Finally, the resulting oil impact and ecosystem services indices are brought together within a bivariate geo-visualisation in order to identify areas of high and low risk of significant ecosystem service loss. For the oil impact index it is stated that the main impacts are on-site infrastructure (Baynard, 2011and Goosem, 2004) thus they were given a higher weight of impact. However, off-site effects can also be of noticeable impact hence an influence area of the infrastructure is assigned to the neighbouring pixels for this index. Major oil infrastructures (i.e. pipelines and oil wells) are assumed to be the main causes of impact of the oil industry and occur on point sites. Roads built and maintained by the oil activities are the drivers of urban development and deforestation hence also included and properly weighed as described below. In terms of the ecosystem services index there were several assumptions and considerations to make. All biodiversity variables were included as number of threatened species due to the intrinsic value of biological diversity within an ecosystem (Eichner and Pethig, 2009). Secondly protected areas are included as Boolean maps since they are, by definition, environmentally important zones where the human impact is null or at least controlled to be at its minimum. Third, tree coverage (as a percentage) and carbon stock (in tonnes/Km^2) help to identify the areas where deforestation processes have not taken place and carbon storage services are of great potential value. Finally, water services are assumed to be locally represented by water balance data (in mm/year), which was calculated using the FIESTA hydrological model (Mulligan and Burke, 2005), resulting in the water available for use at the surface. The weighting of criteria for the analysis was done by adopting the ratio estimation method (Malczewski, 2004). Initially all variables for oil impact (oil pipelines, oil wells, oil concessions, roads and urban areas) were ranked from 1 to *n* in order of their relative weight or impact (i.e. in relation with the other considered variables), assigning 1 to the variable of highest impact and *n* to the lowest. The ecosystem services variables (threatened species of amphibians, birds, mammals and reptiles, protected areas, tree coverage, carbon stock, and water balance) were ranked in the same way in a second group of criteria. Then, for each criterion within both groups a fractional value *fr* is assigned according to the absolute impact of the variable within the pixel ($1<fr<100$). In the next step, a ratio *r* is derived by dividing every fractional value by the maximum fraction value amongst the group (Equation 1)

$$r_i = \frac{fr_i}{\max fr_{i-n}}$$

Equation 1

Where fr_i is the fraction of a variable *i* and max. fr_i corresponds to the maximum value within the range of the variable. From this point an initial weight value is calculated by dividing each ratio by the rank score (Equation 2).

$$w_i = \frac{r_i}{\mathrm{rank}_i}$$

Equation 2

Where w_i is the weight for a variable, r_i is its ratio and rank_i corresponds to the assigned rank for the variable. Finally, a normalised weight ($0.00<w_Z<1.00$) is calculated for each criterion dividing it by the sum of weights (Equation 3).

$$w_Z = \frac{r_i}{\sum w_i}$$

Equation 3

Where w_Z is the final normalised weight for a variable *i*. For the oil impact index interpolation an additional measure was included aiming to show the influence that a particular feature (e.g. oil pipelines, oil wells) has within or around the pixel that it occupies. In the ecosystem services equivalent variables were given equal rank and then weighed using the described method (Table 2). The spatial neighbourhood of influence used for the oil impact index (Table 2, last column) is independent from the weighing process and was assigned according to expert advice (Larrea, M. *pers. comm.*). The influenceis defined by the circular neighbourhood of ratio equal to the number of influencing pixels and in the case of oil wells multiplied by the total of individual wells found within that pixel. Using the normalised weights a raster map was derived by interpolation for every variable. Then they were all added into a resultant map that represents each index from 0 (lowest) to 1 (highest). In a final stage a script brings together both indices, oil impact and ecosystem services and allows theirgeo-visualisation in a bivariate map. For this, each dataset was divided in ten data bins using as break points the Jenks Optimisation Method (ESRI, 2011) and excluding the values of zero since they skewed the histogram and data breaks and allowing to represent the clusters of classes within both datasets. Using the bin information, achoropleth colour scale was derived using the RGB colour model, where two variables can be represented within a bi-dimensional space (after Holland, R. *unpublished code*). Then, the spatial information of every cell is added to the code in order to represent them within the appropriate geographic coordinates.

The automatized script delivers a final bivariate map, which represents the risk of significant ecosystem services loss.

3. Results

A total of 1678 oil wells were mapped in the Western Amazon including Ecuador (59%), Peru (38%) and in very minor extent in Colombia (3%). The major pipelines in the studied countries cover an extension of 11,185 Km, since they all cross mainly from East to West across the Andes towards the Pacific Coast. From this total of major pipelines 30% lies over the Western Amazon crossing major rivers along their way. Additionally, a considerable network of secondary distribution pipelines of smaller diameter is known to be present in the area, although they were not included in this study. The road network in the Western Amazon totals 30,483 Km mainly secondary roads which are a major cause of habitat fragmentation. The oil blocks in the Western Amazon cover an area of 657,000 Km^2 and this corresponds to 74% of the Peruvian Amazon 65% of the Ecuadorian Amazon and only 4% of the Colombian portion of the Amazon. The resulting oil impact index (Figure 1) shows major impacts on the Ecuadorian Amazon particularly in the northern areas, which validates the index since most of the oil development has taken place in these zones during the last 44 years.

Table 2: List of variables and weight calculation for the analysis of the oil impacts and ecosystem services in the Western Amazon

Oil Impact	**Rank**	**Fraction**	**Ratio**	**Weight**	**Normalised weight**	**Influence (pixel)**
Oil pipelines	2	100	1	2	0.27	2
Oil wells	1	100	1	4	0.54	3*x**
Block - concessions	3	50	0.5	0.67	0.09	1
Roads	4	50	0.5	0.5	0.07	2
Urban areas	5	25	0.25	0.2	0.03	1
			Total	7.37	1	
Ecosystem Services						
Threatened spp. amphibians	3	10	0.1	0.03	0.02	
Threatened spp. birds	3	10	0.1	0.03	0.02	
Threatened spp. mammals	3	10	0.1	0.03	0.02	
Threatened spp. reptiles	3	10	0.1	0.03	0.02	
Protected Areas	3	10	0.1	0.03	0.02	
Tree coverage	2	35	0.35	0.18	0.12	
Carbon Stock	2	35	0.35	0.18	0.12	
Water Balance	1	100	1	1	0.66	
			Total	1.52	1	

* The influence within the pixel was multiplied by the number (x) of wells mapped within the cell

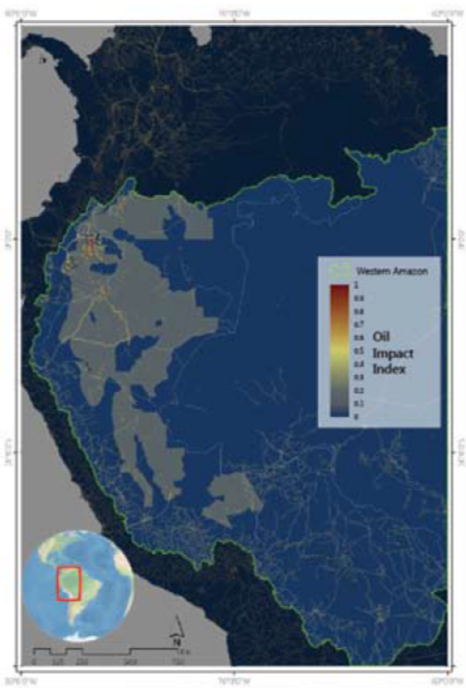

Figure 1: Oil impact index (0-1) for the Western Amazon, at 1 Km resolution

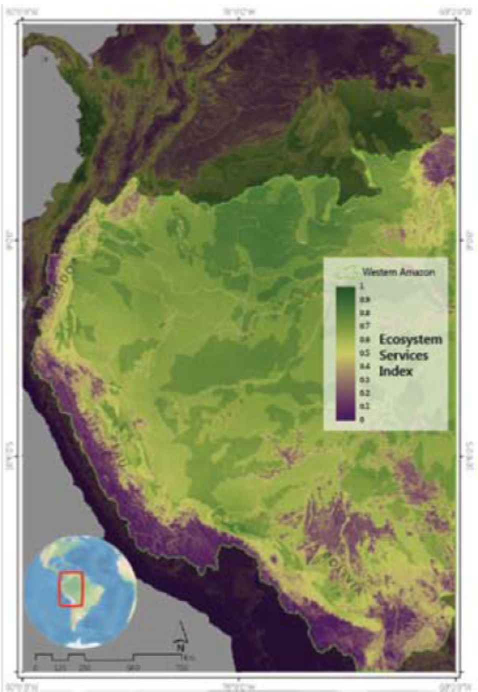

Figure 2: Ecosystem services index (0-1) for the Western Amazon, at 1 Km resolution

The impact is equally high on the Corrientes River area in Peru, where there has been oil extraction for the past four decades. In the Colombian Amazon, the impacts are less significant due to the lower oil development in the area which is used as a control area. High values are also observed along the path of the major pipelines. Statistically, the data distribution shows that up to the third quantile values are close to 0 (mean=0.03), and the top 10% of the values (max=0.91) are due to high on-site localised impacts. Focusing on the resulting maps of ecosystem services index, high numbers of species are concentrated across the whole Western Amazon. Particularly, the highest values for threatened amphibians (up to 133 spp./Km^2) are found in the Yasuni area in Ecuador and the conservation area of Imiria in Peru. Bird species numbers show even higher values in the lower Eastern Andes of Ecuador (735 spp./Km^2) and the Pacaya-Samiria area in north-eastern Peru. For threatened mammals, there is high concentration in the Manu National Park in south-eastern Peru (200 spp./Km^2) and across the lower Andes all the way up to the Amazonas Department in southern Colombia. These values are consistent with the literature (Bass et al., 2010). The protected areas account for a total of 2.3×10^6 Km^2 which represent 26% of the total area of study although the bigger areas are actually located on the extensive Amazon portion of Brazil. Analysing the ecosystem services map (Figure 2), the whole Western Amazon holds great importance with high values (above 0.5) particularly within protected areas due to their high levels of carbon storage and commonly positive water balance, assumed to be the source of good quality drinking water. When looking at the levels of importance in Ecuador the Yasuni National Park and small portion of the Cuyabeno Reserve in the north are of high importance. Equally importance is assigned to the areas of Pacaya-Samiria National Reserve as well as Manu National Park in Peru. Statistically, the data show a bimodal distribution with a third quantile of 0.44 and a maximum value of 0.75 in areas where all ecosystem services are high. When combining both indices and geo-visualising them in a bivariate map, the areas of north-eastern Ecuador and northern Peru show higher levels in both oil impact and ecosystem services indices. This fact was not considered when the oil facilities and infrastructure were located in the middle of the rainforest areas which have been recognised to contain high biodiversity levels (Bass et al., 2010) and proven to be the source of ecosystem services (Ojeda et al., 2008, Eichner and Pethig, 2009 and Mulligan, 2010a). Furthermore, it is important to look at the areas with high levels of ecosystem services (above the third quantile) and in the medium range of the oil impact index which are areas that have not been "oil developed" but are included in plans of future developments. These areas clearly have a high risk of ecosystem service loss and in general they coincide with protected areas and indigenous territories that overlap with oil concessions.

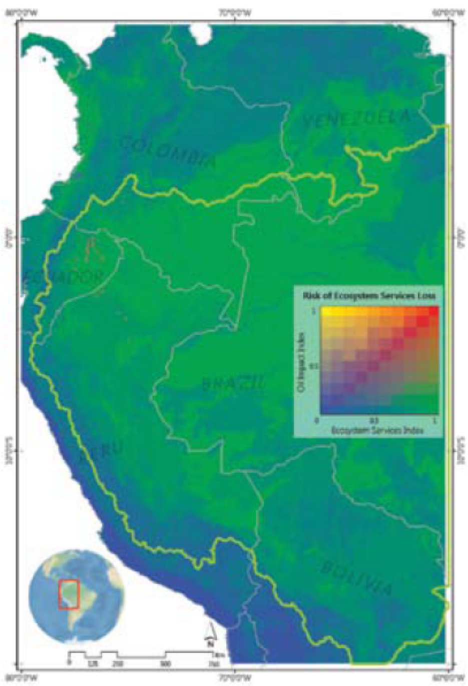

Figure 3: Risk of ecosystem services loss (0-1) obtained combining in a bivariate space both oil impact and ecosystem services indices, for the Western Amazon, at 1 Km resolution

4. Discussion and Conclusion

A comprehensive GIS analysis of oil infrastructure potential for impact and environmental importance has not been performed in such detail for the whole of the Western Amazon. Finer et al., (2009) successfully described the oil situation by mapping the oil concessions but further and more detailed work was needed to evaluate the actual extent of the impact. Furthermore, identifying areas of risk of ecosystem service loss due to oil activities is a step forward towards a cleaner and more environmentally sound extraction of resources. Applying new techniques of geo-visualisation proved to be an innovative approach to bring variety scientific information within a single map. The resulting maps were discussed with experts from both the environmental and industry fields, and there is a general agreement, and hence validation, on the extent of impact and the importance of the potential ecosystem services that the areas hold. As a regional study the information produced can help to better understand the current trans-national situation of oil in the region beyond the official reports from the environmental agencies in each country. Additionally, the reliability of the indices is supported by objective and independent scientific data. Consequently, the results can effectively be of use and application on informed decision and policy making. Open and public information may be of use and support to all stakeholders, from oil companies, local governments, civil organisations through to indigenous communities living and depending on the land, its resources and its ecosystem services. Currently, Ecuador and Peru are signing agreements to extend the oil frontier across their borders by integrating the North-Peruvian pipeline with the oil concessions to be exploited in South-eastern Ecuador (Presidency of Ecuador, 2012). For these reasons, the need for independent sources of scientific information is greater. This study contributes to that need by bringing scientific information within a spatial context and making it available, through innovative technology, in an understandable and approachable way.

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Appendix C

Supplementary material

This section presents supplementary material to the research paper titled 'Multicriteria GIS Analysis and Geo-Visualisation of the Overlap of Oil Impacts and Ecosystem Services in the Western Amazon'. It looks to further explain the Methods section, thus it covers subsections on the data used for the analysis, as well as the equations and weighting process applied with examples. At the end, the script developed in R language by the author for the final choropleth raster map is presented in full.

Data

Public sources of information were used at first instance for the identified variables of interest. For the **oil and gas infrastructure** datasets, sources were variable in terms of coverage and availability. For every country included in the study, the governmental agency and the national oil company were found to be a reliable source of updated information. However, most of their data was not readily available. Hence, part of the efforts during the field season were dedicated to research, contact, and retrieve this information directly from the institutions within the country. Particularly in Ecuador, a letter of intent had to be signed with the national oil company, Petroecuador, for the release of the information, though it included additional field activities that help in this and further parts of the research of this thesis. As above mentioned, in the Methods section of this paper, only data covering the whole area of study was included, which meant that some relevant information such as waste pits, gas flares, and oil spill sites, had to be left out of the general study since they were only available for Ecuador's territory. At the end, the *oil impact index* was calculated with parameters of infrastructure including: oil wells, oil pipelines, oil and gas concessions, roads and urban areas.

On the other hand, for the environmental variables, the main source of information was the **SimTerra database** (Mulligan, 2010), a global database of environmental variables that contains gridded coverage of the terrestrial world at less than or equal to 1Km resolution (http://www.policysupport.org/simterra). For the purpose of this study the database was queried and the relevant variables retrieved. For every variable of interest there was a total of six tiles that were downloaded, resampled and post-processed in ArcGIS 10 (ESRI, 2011) before they can be utilised for the analysis. The *ecosystem services index* was calculated using the most relevant proxies to represent them, including variables of local water balance, carbon stock, tree coverage, protected areas and biodiversity. Protected areas were included as part of the analysis to take into account the relevant and healthy ecosystems they protect, which are sources of potential ecosystem services. Similarly, biodiversity is included since it is considered a vital and supporting part of all ecosystems' processes. Furthermore, taking into consideration that oil and gas extraction is a potential threat to biodiversity, the most representative data to include were the IUCN red lists for mammals, birds, reptiles and amphibians; as they indicate threatened biodiversity.

Since the publication of this paper there has been new research that improved the understanding at a global level of the risk of fossil fuel extraction on biodiversity. Butt et al., (2013) took into account the amount of barrels of oil in reserve and compared them with species richness and threatened species datasets in order to identify areas of overlap and resulting higher risk. Similarly, Osti et al. (2011), contributed with their GIS study of oil and gas developments overlapping with protected areas and world heritage sites in sub-Saharan Africa. Furthermore, Finer et al. 2010, carried out a similar overlay analysis of oil and gas concessions with protected areas and indigenous territories within the Western Amazon. My contribution to all the mentioned studies relies on the aggregation of all relevant parameters in one final index, which is not just overlaying datasets but giving them an assigned weight and yielding an spatial result visualised in an innovative two-axis plot.

Equations and Weighting Process

The weighting process was based on the method originally proposed by Malczewski (2006) for land use suitability analysis. It was adapted for the specific purpose of the current research question. The equations were modified and applied with the data as presented in the main paper. In this subsection, an example is presented as how the actual values of the study were calculated, and the assumptions and caveats of this process.

To mention one case, the oil wells dataset was ranked as the most impacting infrastructure of oil and gas extraction, hence it was ranked number 1 (rk=1). Within the pixel an oil well occupies, the fractional coverage it will impact was assigned to 100%, since it was observed from aerial images and field visits that a common oil well has an influence of approximately 400-500 m., around the point site, thus fr=100. The ratio divides the fractional value by the rank value. In the example, the oil wells have maximum fractional value and are ranked first, so the result equals to the maximum (r=100). Then, the weight is calculated with this ratio divided by the minimum fractional coverage, which for the oil wells is 100/25 = 4 (w=4.00). Note that the minimum fractional coverage was assigned to urban areas, 25%, since it was assumed that their influence is related but not immediate to the oil and gas extraction activities. Finally, the normalised weight is calculated with the division of the weight by the sum of all weights, which for the oil wells is 4.00/7.37=0.54 (w_Z=0.54). The weighting process is not completely objective, but it tries to include all relevant variables according to the impact they may cause in the ground. At the end, every pixel that has an oil well will be assigned a value of 0.54 in the oil impact index. Theoretically, a pixel may be occupied by all the weighted oil and gas infrastructure parameters, thus it would have an index value equal to 1.

Script code for R

The script was written in the programming language for `R` Statistical Package, utilising the `maptools` library and `gdal` plotting capabilities as main tools. As cited in the paper, the code was based on the work of Rob Holland, from the University of Southampton, who kindly shared his original code to start with. The script originally worked only with vector datasets (i.e. shapfiles), so I adapted it to use the raster (i.e. ASCII files) that were produced from the earlier multicriteria analysis. Ultimately, the operational code yielded the map for risk of ecosystem services loss presented in the paper.

APPENDIX D

LIST OF VARIABLES USED IN CO$TING NATURE POLICY SUPPORT TOOL, PROVIDED BY THE SIMTERRA DATABASE, EXTRACTED FROM THE POLICY SUPPORT SYSTEM

Data is presented as a list and organised alphabetically using the Description field

Module	Description page 1 of 3
97	Accessibility
177	All mineral deposits
101	Alliance for Zero Extinction site (2012)
119	Area of water bodies upstream
121	Area of wetlands upstream
69	Biodiversity hotspots (Conservation International)
26	Carbon stock
27	Cell area
28	Cereal crop fraction
81	Change in tree cover (2000-2010)
176	Coal bearing areas
135	Coastline (SWBD)
68	Coral presence
23	Cover of bare ground (Landsat/MODIS 2000)
24	Cover of herb-covered ground (Landsat/MODIS 2000)
25	Cover of tree-covered ground (Landsat/MODIS 2000)
59	Croplands (2000)
39	Dams
106	DMSP Night-time lights (2000)
129	Downstream cropland
127	Downstream irrigated area
125	Downstream land area
131	Downstream population
133	Downstream population considered poor (<$2 per day)
57	Dry matter productivity
70	Ecoregions (WWF)
1	Elevation (Hydrosheds)
73	Endemic bird areas (Birdlife International)
65	Endemism richness for (IUCN redlist) amphibians
146	Endemism richness for (IUCN redlist) birds
63	Endemism richness for (IUCN redlist) mammals
181	Endemism richness for ferns
66	Endemism richness for reptiles
46	FAO irrigation percentage
29	Fibre crop fraction
141	Floodplain area downstream

Module	Description page 2 of 3
140	Floodplain area upstream
30	Forage crop fraction
103	Forest loss since pre-human times
102	Frequency of fire burn events
31	Fruit crop fraction
77	GDP projection (SRES B2 scenario) 1990
78	GDP projection (SRES B2 scenario) 2025
71	Global 200 ecoregions (WWF)
44	Globcover land use classes
74	Important bird areas (Birdlife International)
100	Key biodiversity areas (2012)
72	Last of the Wild
16	Local drainage direction (Hydroshed..
49	Managed grazers (2005)
115	Mangroves (1997, UNEP-WCMC/ISME)
179	Mean rainfed crop suitability (high inputs)
178	Mean rainfed crop suitability (low inputs)
120	Mean slope upstream (>10 deg)
152	Mining concessions
114	MODIS water mask
122	Number of dams downstream
118	Number of dams upstream (GOOD)
117	Number of observed tsunami since 2000BC (NGDC)
104	Number of panoramio photos (November 2010)
150	Oil and gas concessions
32	Oil crop fraction
33	Other crops fraction
60	Pastures (2000)
175	Percentage of population considered poor (<$2 per day)
151	Planned transportation routes
48	Population (2007, Landscan)
76	Population projection (SRES B2 scenario) 1990
75	Population projection (SRES B2 scenario, world pop 8.039 billion) 2025
79	Presence of mines
80	Presence of oil and gas wells
61	Protected areas (UNEP-WCMC WCPA) 2012
137	Protected areas downstream (WDPA)
136	Protected areas upstream (WDPA)
143	Protected floodplain area downstream
142	Protected floodplain area upstream
34	Pulses crop fraction
93	Rainfall accumlated down flow lines (Hydro1k)
116	Relative cyclone hazard frequency index (CHRR)
110	Roads (GAUL)

Module	Description page 3 of 3
35	Root and tuber crop fraction
174	Rural populated places
149	Soil carbon
64	Species richness for (IUCN redlist) amphibians
147	Species richness for (IUCN redlist) birds
62	Species richness for (IUCN redlist) mammals
180	Species richness for ferns
67	Species richness for reptiles
15	Study area (Hydrosheds)
36	Sugar crop fraction
107	Terra-i land cover change
14	Total annual precipitation
139	Total tree cover downstream
138	Total tree cover upstream
105	Touristiness (photos by different users per unit area)
37	Trees and nuts crop fraction
55	Underweight population under 5 years old
128	Upstream cropland
126	Upstream irrigated area
124	Upstream land area
130	Upstream population
132	Upstream population considered poor (<$2 per day)
123	Upstream relative cyclone hazard frequency index (CHRR)
58	Urban Areas
38	Vegetables and melons crop fraction
92	Water balance (WorldClim rainfall - CPWF AET)
134	Water bodies (SWBD lakes)
111	Wetlands including lakes, rivers and reservoirs
50	Wildland grazers headcount (2005)
109	17 model mean precipitation change to 2050s (IPCC SRES A2a)
108	17 model mean temperature change to 2050s (IPCC SRES A2a)

APPENDIX E

Extract from the paper manuscript: “Globally relative but locally relevant nature conservation priorities with Co$ting Nature: Concepts” by Mark Mulligan, King’s College London

THE CO$TING NATURE TOOL

BACKGROUND

Co$ting Nature assumes that conservation and development priority should be defined on the basis of data for ecosystem services, biodiversity, current pressure and future threat as well as the delphic (expert) prioritizations which already exist. Clearly the development value of land is also critical, especially suitability for agriculture and potential productivity as well as the potential value of the available natural resources. These values need to be seen within the context of the costs of developing and maintaining their production or extraction but also relative to conservation priority: for example the trade-off between protection of a high conservation value area and its value for rare-earth mineral mining may be different to the tradeoff between high conservation value and low-productivity agricultural development potential. Co$ting Nature V2.x * focuses on assessing conservation priority and the tradeoffs between protection of different ecosystem services, biodiversity and threatened places and does not examine the trade-offs between benefits from conservation and benefits from developmental land uses.

POTENTIAL AND REALIZED ECOSYSTEM SERVICES

We make the distinction between environmental and ecosystem services and between potential and realised ecosystem services (see Mulligan et al., 2010). Environmental services are considered here to represent those services provided by the environment and not necessarily manageable through land use management: for example cloud affected forests that occur on tropical mountains are considered to provide significant water resources to downstream communities. This is in part because these forests occur in high rainfall, headwater areas which are also exposed to frequent cloud and fog, meaning that solar radiation, temperature and thus evaporation are low compared with lowland forests (Mulligan and Burke, 2005; Saenz and Mulligan, 2013). Cloud affected forest environments thus do provide significant water resources but this is a function of the climate in which they occur rather than the cloud forest ecosystem itself. On the other hand cloud affected forests also receive inputs of water from cloud water interception (*CWI, sensu* Bruijnzeel et al., 2011). This is additional to the rainfall received and is greater to forests than to pastures because of the higher leaf and epiphytic surface area of forests. CWI is truly an ecosystem service: if the forest ecosystem is replaced with low pasture then this input of water decreases: land use and management impact the delivery of this service and it is thus manageable at the local scale.

We also make the distinction between potential and realised ecosystem services. Potential services are provided but not necessarily received by human beneficiaries. For example a cloud affected forest may provide volumes of clean water but if there are no populations downstream to receive this water then the service is only potential (provided but not used).

The potential service should not be ignored since it may be realised in future through population growth or infrastructural development downstream. Moreover, it may already support non-human benficiaries such as riparian ecosystems. Realised services are produced and also consumed by (proximal or distal) beneficiaries. For carbon storage and sequestration all potential services are also realised since all carbon sequestered benefits us all in mitigating climate change. However for water, hazard mitigation and nature-based tourism, for example, the patterns of potential and realised ecosystem services are very different since realised services reflect the distribution of beneficiaries in the landscape.

There are many ecosystem services (Costanza et al*.,* 1997; De Groot et al., 2002) but not all can be mapped globally since many are highly complex and poorly understood or difficult to measure. Here we focus on key provisioning, regulating and cultural services: in particular water quantity and quality (provisioning), carbon storage and sequestration (regulating), hazard mitigation (regulating) and nature based tourism (cultural). We map the sites of production of these services since our focus is on managing those sites. But, to distinguish between potential and realized services we also map human beneficiaries who may be local (hazard mitigation), downstream (hazard mitigation and water), or global (carbon storage and sequestration).

Co$ting Nature produced four key outputs:
(a) Relative aggregate nature conservation priority index (potential services) captures pressured and threatened conservation priority areas with high potential service provision.
(b) Relative aggregate nature conservation priority index (realised services) captures pressured and threatened high biodiversity areas with high realized ES provision.
(c) Relative aggregate development priority index (potential services) captures already pressured areas with low conservation priority and potential service provision.
(d) Relative aggregate development priority index (realised services) captures pressured areas with low conservation priority and realised service provision.

These metrics are calculated from metrics covering delphic conservation priority, biodiversity, ecosystem services, current pressure and future threat.

Delphic conservation priority

We calculate delphic conservation priority (Dc) as the normalised mean of the presence of Endemic bird areas, global 200 ecoregions, conservation hotspots, important bird areas, last of the wild areas and key biodiversity areas. Thus a pixel that falls in all of these prioritisations will have the value 1 whereas a pixel that is covered by 3 out of 6 has the value 0.5. These six prioritisations cover a range of proactive and reactive schemes (Brooks et al., 2006) for which data are publicly available. This metric attempts to capture conservation priorities that are not captured by the remaining metrics.

Ecosystem services

Ecosystem services can be estimated in biophysical units, but these units cannot easily be combined to assess the bundle of services at a site. Some authors combine services by converting them to a common economic currency through valuation (Costanza et al*.,* 1997; Troy and Wilson, 2006), others present them separately (Raudsepp-Hearne et al., 2010). Here we combine services by expressing each as a normalised value between the globally or the locally highest and lowest values. The normalised values (expressed in values of 0-1) can then be combined irrespective of their units. The analyst can define whether values are normalised to a global maxima as would be necessary for global comparisons or local maxima to more clearly highlight local patterns.

Carbon

Carbon storage and sequestration are distinct services. Carbon stored in vegetation and soil is locked out of the atmospheric system for a period and this contributes to their being less carbon in the atmosphere. Carbon storage is not an active service of the ecosystem but rather a consequence of carbon sequestration and of the ecosystem remaining intact so that carbon accumulates. Carbon sequestration is determined by photosynthesis and accrues continuously so the magnitude of the service increases over time, contributing to carbon stocks in the process. The total carbon service is thus the combination of carbon stocks and carbon sequestration and the balance between the two clearly depends on the time period over which sequestration is calculated. Carbon sequestration is calculated here from the dry matter productivity (DMP) analysis of Mulligan (2009b) in which SPOT-VGT DMP[1] calculated every 10 days at 1km resolution on the basis of change in NDVI, was averaged over the period 1998-2008, globally. DMP (t biomass/ha/yr) is multiplied by 0.42 (Ho, 1976) to convert to units of tC/ha/yr. Above-ground carbon stock is calculated from Saatchi et al. (2011) for the areas in which data are available and Ruesch and Gibbs (2004) elsewhere. This is combined with soil carbon calculated from the map of Scharlemann et al. (2009) to produce total above- and below-ground carbon stocks. The potential (Cp) and also realised(Cr) carbon service is thus the mean of normalised carbon sequestration (Cs), normalised above-ground carbon stocks (Ca) and normalised below-ground carbon stocks (Cb) (eq 1 and 2). This is multiplied by the analyst-defined prioritisation weight for carbon (SWc) which (as with all analyst-defined weights) defaults to 1.

$$Cp=((Cs+Cb+Ca)/3)*SWc \qquad \text{(eq 1)}$$

$$Cr=Cp \qquad \text{(eq 2)}$$

Water

Water is considered a provisioning service here, though it also plays a role in the regulating services (see section on hazard mitigation). Potential water services are measured as the volume of runoff (rainfall minus evapotranspiration) whose quality is unaffected by human activity, cumulated downstream. This is an indicator of the volume of clean water produced by a pixel (Ws). The human footprint on water quality index (HF) (Mulligan, 2009) is used as the indicator of water quality. The HF considers particular land uses to have the potential to contaminate water with sediment, agrochemicals, manures *etc*. Land uses such as unprotected agriculture and pasture are considered non-point sources and roads, mines, oil and gas wells and urban areas are considered point sources. Agriculture in protected areas and areas with no human land use are considered to have a human footprint of zero. The HF index multiplies the water balance of a pixel by the fractional cover of point and non-point sources in that pixel and cumulates this 'polluted' water downstream using a streamflow network. The total volume of water flowing is also cumulated downstream and

[1] The BioPar DMP product is developed by VITO in the framework of the MARS FOOD project. It is generated from the SPOT VEGETATION data under copyright CNES and distribution by VITO.

the HF in a pixel becomes the polluted water as a percentage of the total water flowing. This is calculated globally and read as input to the model. The non-polluted volume of water expressed as a fraction is considered the potential water service (Wp) of a pixel. Realized water services (Wr) are calculated in a very different way, considering the distribution of beneficiaries for hydrological services. Maps of normalised downstream population, irrigation area and number of dams are pre-calculated globally to represent the distribution of beneficiaries. Population (P) is derived from Landscan (2007) and is summed downstream at 1km resolution using a drainage network derived from HydroSHEDS (Lehner et al., 2008) using PCRaster[2] with the downstream total for a pixel assigned to that pixel. For number of dams (D) we use the global dam census of Mulligan et al. (2011) and for irrigated land (I) we cumulate the downstream irrigated areas of Siebert et al. (2007) for each point. These provide pixel-level indicators of the distribution of the beneficiaries of hydrological ecosystem services at a much finer resolution than previous global studies. The potential and realised services are multiplied by the analyst-defined priority weighting for water (SWw), which defaults to 1. Where the analyst requests normalisation to local rather than global maxima then the realised water services map is normalised.

$$Wp=Ws*SWw \quad \text{(eq 3)}$$

$$Wr=Ws*((P+I+D)/3)*SWw \quad \text{(eq 4)}$$

where: ****

Nature based tourism

For nature based tourism, we again separate potential tourism services from realised tourism services. Potential services are defined on the basis of delphic conservation priority (Dc) and accessibility (travel time) to major population centres, assuming that those areas that the conservation organisations consider important are also potentially attractive for nature based tourism. In addition to Delphic conservation priority, we used normalised slope steepness (S) as an indicator for scenic beauty and normalised water services (Ws) as an indicator of the abscence of human footprint (agriculture, industry, litter, pollution).

Accessibility is taken from the global grid of Uchida and Nelson (2009), normalised and then subtracted from 1 to give accessibility instead of travel time. The distance decay function for population with access (Pa) is calculated using a friction weighted distance from all urban centres (defined from Schneider et al., 2009) where the initial ‘friction’ is the normalised population (according to Landscan) of the urban centre and the per-cell ‘friction’ is defined according to the normalised population multiplied by normalised accessibilty. This index captures the distance decay of population having access to the area (closer populations have greater access than those further away, though closer populations may have fewer people than more distant ones). Since we wish to capture rural nature based tourism only, the tourism value is calculated only for non urban areas (urban=0 or normalised population <0.95 to capture density populated areas not considered urban by Schneider et al. 2009). The potential and realised services are multiplied by the analyst-defined priority weighting for tourism (SWt).

$$Tp = Pa*((Dc+S+Ws)/3)*SWt \quad \text{(eq 5)}$$

[2] PCRaster environmental software, www.pcraster.nl

Realized nature-based tourism services are estimated from the density of georeferenced photographs outside of urban areas that were available in the Panoramio photo archive in * 20**. These are assumed to equate with high value nature based tourism. A value of 'touristiness' was calculated as the number of Panoramio photos by different authors in 0.25 degree tiles globally following the method that Heinla (2010) applied at 0.5 degree resolution. The results are masked to exclude urban areas according to the urban areas map of Schneider et al. (2009).

Hazard mitigation

Hazard mitigation services are perhaps the most complex to assess since they are a function of:

(a) the potential for multiple hazards to occur and the human and infrastructural exposure to those hazards, vulnerability to negative impacts of hazards. Exposure and vulnerability together define the risk.

(b) the role of local, upstream or near-coast ecosystems in reducing the potential impact of hazards (potential hazard mitigation services).

Realised hazard mitigation ecosystem services are then defined as those areas in which ecosystems provide hazard mitigation services but where there is also risk. Areas with no risk may receive potential hazard mitigation services but these services are not realised. Hazard potential is determined as:

(a) the normalised frequency of cyclones according to (Dilley et al., 2005) multiplied by the normalised water balance as a measure of high magnitude rainfall event hazards;

(b) for coastal inundation hazards we calculate distance from coast according to USGS (2006) and consider all pixels within 2km as coastal (Co). We also produce an index of lowlying land as: LL=1-(E/30) for all areas from 0 to 30m elevation (E) according to the SRTM digital elevation model post-processed by Lehner et al. (2008). Probability of (coastal) inundation hazard is considered proportional to the normalised probability of Tsunami, Tsu, (according to NGDC, 2011)**, cyclones, Cyc, and climatic sea level rise (considered for simplicity as equally likely i.e. 1.0 everywhere) for all coastal areas. The probability of indundation hazard thus becomes:

$$HIn=(Tsu+Cyc+1.0)/3)*LL*Co, \qquad \text{(eq 6)}$$

(c) for landslide hazards we consider the probability of landslides to increase with the normalised mean upstream slope gradient. Upstream slope gradient is pre-calculated using the 1km resolution digital elevation model and flow network of Lehner et al. (2008).

(d) the potential for flooding is considered proportional to normalised water balance with small potential in dry areas and high potential where water is plentiful. Though many floods are fluvial in nature, we use water balance rather than runoff in recognition that floods also occur from overwhelmed urban drainage, groundwater flooding and rainfall intensity greater than infiltration rates. These latter types of flood can be somewhat more predictable than fluvial floods.

Hazard potential is thus the mean of cyclone, indundation, landslide and flood probabilities, normalised either locally or globally. In addition to hazard potential, we consider hazard exposure as the exposure of human populations, activity and infrastructure. Socio-economic exposure is calculated as normalised GDP for 1990 (CIESIN, 2002), population

(Landscan, 2007), agriculture (cropland and pasture fractional areas from Ramankutty, 2008). and infrastructure. Infrastructural exposure is calculated as the sum of the presence of dams (Mulligan et al., 2011), mines (Mulligan, 2010a), oil and gas (Mulligan, 2010b), urban areas (Schneider et al., 2009) and roads (FAO, 2010). Exposure is multiplied by hazard potential to produce the index of exposure to hazards.

Vulnerability to hazards is considered to scale with normalised GDP and infrastructure: the greater the GDP and infrastructure, the greater the capacity to cope with hazards. Risk (R) is then exposure (E) multiplied by vulnerability (V). This is multiplied by the analyst-defined prioritisation weight for hazards (FWh), which defaults to 1.

$$R=E*V*FWh \qquad \text{(eq. 7)}$$

Potential hazard mitigation services are then calculated according to a series of assumptions, based on knowledge of how ecosystems mitigate these hazards. We assume that landslide (LS) impacts at a point are mitigated according to the proportion of upstream area that is tree covered (using tree cover data from Hansen et al., 2006) or protected (WDPA, 2012). This because tree cover reduces potential soil waterlogging and has been shown to reduce landslide frequency - ref* and protected areas will tend to have a lower agricultural and infrastructural impact - both of which can lead to increased frequency of landslides. Regulation (RE) of drought hazards (for example reduced dry season flows) are assumed proportional to tree cover upstream. Although trees evaporate significant volumes of water and thereby reduce flows, they also encourage infiltration that helps to maintain dry season flows (pena*). Flood hazards (FL) are mitigated according to the proportion of upstream area that provides flood storage in the form of trees, wetlands (Lehner and Doll, 2004), water bodies (USGS, 2006) and floodplains (Mulligan, 2010). Mitigation from coastal inundation (CI) is considered to be provided by wetlands and mangroves (Spalding et al., 1997) but only in lowlying and coastal areas. Where they occur inland they are assumed to have no coastal inundation mitigation potential. The total potential hazard mitigation services is the mean of coastal, floods regulation and landslide mitigation services. This is multiplied by the analyst-defined prioritisation weight for hazards (FWh), which defaults to 1.

$$HMp=((CI+FL+RE+LS)/4.0)*FWh \qquad \text{(eq. 8)}$$

Realised hazard mitigation (HMr) services are calculated as the minimum of risk (R) and potential hazard mitgation srevices (HMp) for areas where risk is greater than 0. In other words if HMp is greater than risk then HMr equals risk and the remaining HMp is unused. If risk is greater than HMp then HMr is equal to HMp and some risk remains unmitigated.

BIODIVERSITY

Focusing on ecosystem services alone ignores the reality that biodiversity is an important factor determining nature conservation priority since it has intrinsic value (Oksanen 1997; Ghilarov, 2000; Justus et al., 2009). Biodiversity also supports a range of ecosystem services including pest control (Bianchi et al. 2006), ecosystem stability (Tilman et al., 2006) and plant genetic resources. The most conservation relevant measure of biodiversity is difficult to define: ecosystem diversity, genetic diversity, taxonomic diversity and evolutionary distinctiveness are all candidates but given data constraints most studies use a measure of species richness (Purvis and Hector, 2000). In Co$ting Nature we combine a measure of species richness with a measure of species endemism. Endemism captures rarity, which is clearly of conservation relevance in addition to species richness.

Species Richness

We use the IUCN sampled redlist extent of occupancy (EOO) data for amphibians (IUCN, 2008), mammals (IUCN, 2008b), reptiles (IUCN, 2010) and birds (Birdlife, 2012) and calculate a measure of richness (total number of sampled species within each 10km) combining all sampled species. We would have liked to incorporate similar data for plants but these data are not in the public domain.

Endemism Richness

Kier and Barthlott (2001) define endemism richness as the "specific contribution of an area to global biodiversity". Since it accounts for range size rarity, it is potentially a better measure of conservation value than species richness. The contribution of a specific area to the global species inventory is known as its C-value. For the 10 by 10 km (native) raster grids used here the C-value of a pixel for a given species was calculated as 1/G, where G is the global range size (i.e. the number of pixels in which the species occurs). Thus where species have a large range, the C-value is low, and where their range is restricted, the C-value is high and endemism richness of a site is thus the sum of C-values for all the species for which data are available. The species and endemism richness metrics are both normalised and then combined into a single biodiversity metric.

PRESSURE

Current pressure of human activity is calculated according to the mean of normalised values for recent land use change (*luc*), human population density (*pop*,Landscan, 2007) , fire frequency calculated from 10 years of the MODIS burned area product (*firefreq*, Mulligan, 2010), grazing intensity for both wildland and managed grazers (*grazing*, Wint and Robinson, 2007), agricultural intensity for pastures and croplands (*ag*, Ramankutty, 2008), dams (*dams*, Mulligan et al., 2011) and infrastructure (*infra*, upstream dams and local mines, oil and gas, urban areas and roads). Recent land use change is calculated as having occurred where either MODIS VCF 2010 (Townsend et al., 2011) is more than 40% lower than MODIS VCF 2000 (Hansen et al., 2006) in the majority of pixels in a square window of 3 pixels around each cell or where MODIS terra-i[3] data indicates land use change. Pressure is then calculated as the mean of each of these factors. This is multiplied by the user-defined prioritisation weight for pressure (FWp), which defaults to 1.

P=(luc+pop+firefreq+grazing+ag+dams+infra)/7.0)*SWp (eq. 9)

THREAT

In addition to current pressure, conservation priority also depends on how such pressure may change into the future, *i.e.* threat. We calculate threat according to planned infrastructure (*plan*), presence of resources (*res*), relative accessibility from towns of 50,000 population (*acc*, Uchida and Nelson, 2009), relative proximity to the recently deforested areas defined for the pressure metric, *proxdefor* (*i.e.* deforestation fronts),

[3]www.terra-i.org

relative projected change in GDP and population between 1990 and 2025 (*gdpch*, CIESIN, 2002), relative projected change in climatic temperature (*tempch*) and precipitation (*precch*) to the 2050s (for IPCC SRES A2a ensemble mean of 17 GCMs) and the relative current distribution of night-time light intensity (*lights*) as an indicator of otherwise undefined threats (Elvidge et al., 1997). We use global maps of mining and oil and gas concessions derived from multiple national and international sources alongside a global map of planned roads derived from multiple sources to define areas where infrastructural change is planned or likely. As an indicator of the availability of resources, we include near global coal bearing areas (Tewalt et al., 2008; Merrill et al., 2008), all mineral deposits (USGS, 2011), mean suitability for 48 crops (low inputs) and mean suitability for 48 crops (high inputs). All of these factors are normalised and combined into a single metric which is then multiplied by the user-defined prioritisation weight for threat (FWt) which defaults to 1.

$$T = ((plan+res+acc+proxdefor+gdpch+popch+tempch+precch+lights)/9)*FWt \qquad \text{(eq. 10)}$$

SUMMARY METRICS

In addition to the bundled ecosystem service, biodiversity, pressure, threat and delphic metrics we calculate a series of compound metrics that define overall conservation and development priority:

(a) Relative aggregate nature conservation priority index (potential services) captures pressured and threatened conservation priority areas with high potential service provision. These areas may not be important in providing realised services now, but have the potential to do so. This is calculated as the mean of metrics for threat, pressure, the potential ecosystem services, biodiversity and delphic conservation priority, each weighted by the analyst-defined service or factor weight, all of which default to 1.0 It is masked for rural areas only as many of the ecosystem services calculated are of little relevance to urban contexts.

(b) Relative aggregate nature conservation priority index (realised services) captures pressured and threatened high biodiversity areas with high realized ES provision. These are high priority and also important in providing services that are realised now. This is calculated as the mean of the metrics for threat, pressure, the realised ecosystem services, biodiversity and delphic conservation priority, each weighted by the analyst-defined service or factor weight, all of which default to 1.0. It is masked for rural areas only as many of the ecosystem services calculated are of little relevance to urban contexts.

(c) Relative aggregate development priority index (potential services) captures already pressured areas with low conservation priority and potential service provision. These areas are suitable for development since they are already pressured and not likely to provide ecosystem services into the future (if potential services are low then realised services will also be low) and they are also of low conservation priority. This metric is calculated as the mean of pressure and the inverse of biodiversity, delphic priority and potential services, all weighted for user-defined factor and service weights, which default to 1.0. Where conservation priority is low and pressure is high, development priority will be high.

(d) Relative aggregate development priority index (realised services) captures pressured areas with low conservation priority and realised service provision. These areas are again suitable for development on the basis of existing high pressure and low conservation priority and realised ecosystem service provision. It is calculated as for the previous metric but using the realised ecosystem service metric. Realised ecosystem service provision may be low because potential provision is low or because there are few people nearby or downstream to benefit from the provided services. This metric should therefore be used with caution because further development of low realised ecosystem .service areas implies growth in human population and infrastructure nearby which will increase realized ecosystem services so long as the potential services are there to be realised.

APPENDIX F

COSTING NATURE 1KM RUNS WITHIN THE PSS

(www.policysupport.org/costingnature)

178.155 Use: | ecoengine for: **costingnature v.2 [.48dev]** [non-commercial use] | Help | Disclaimer |

You are storing a total of **9** runs (baselines and alternatives) at different spatial resolutions across all PSS from a maximum of **9**

If you are experiencing problems with the system then delete all old runs using the next link as some may no longer be compatible with the system

Delete all runs (including current) from all PSS

Delete runs older than 1 day old from all PSS

Delete runs older than 1 week old from all PSS

Here is a list of previous **baseline** runs of type **tiled/1-square-km** and origin **leozurita_gmail.com**.Click the relevant links to view or choose a run

SimTerra tile number: __10__12.corr.map.gz
Baseline run: brasil

username :	leozurita_gmail.com
runname :	brasil
model_version :	2.[.48dev]
runtype :	tiled/1-square-km
bbox_north :	-0.0
bbox_south :	-10.0
bbox_west :	-70.0
bbox_east :	-60.0
date_created :	(2014, 2, 19)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	
current_zoi :	

Centre coordinates: -5.0,-65.0
Choose this baseline
Delete this baseline (and associated alternatives)

SimTerra tile number: __9__11.corr.map.gz
Baseline run: col

username :	leozurita_gmail.com
runname :	col
model_version :	2.[.48dev]
runtype :	tiled/1-square-km
bbox_north :	10.0
bbox_south :	0.0
bbox_west :	-80.0
bbox_east :	-70.0
date_created :	(2014, 1, 9)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	
current_zoi :	

Centre coordinates: 5.0,-75.0

Choose this baseline
Delete this baseline (and associated alternatives)

SimTerra tile number: __11__11.corr.map.gz
Baseline run: pe

username :	leozurita_gmail.com
runname :	pe
model_version :	2.[.48dev]
runtype :	tiled/1-square-km
bbox_north :	-10.0
bbox_south :	-20.0
bbox_west :	-80.0
bbox_east :	-70.0
date_created :	(2014, 1, 26)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	
current_zoi :	

Centre coordinates: -15.0,-75.0
Choose this baseline
Delete this baseline (and associated alternatives)

SimTerra tile number: __11__12.corr.map.gz
Baseline run: boliv

username :	leozurita_gmail.com
runname :	boliv
model_version :	2.[.48dev]
runtype :	tiled/1-square-km
bbox_north :	-10.0
bbox_south :	-20.0
bbox_west :	-70.0
bbox_east :	-60.0
date_created :	(2014, 1, 7)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	
current_zoi :	

Centre coordinates: -15.0,-65.0

Choose this baseline

Delete this baseline (and associated alternatives)

SimTerra tile number: __10__11.corr.map.gz
Baseline run: ec

username :	leozurita_gmail.com
runname :	ec
model_version :	2.[.48dev]
runtype :	tiled/1-square-km
bbox_north :	-0.0
bbox_south :	-10.0
bbox_west :	-80.0
bbox_east :	-70.0
date_created :	(2013, 11, 13)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	unknown
current_zoi :	oil1011zip

Centre coordinates: -5.0,-75.0

Choose this baseline
Delete this baseline (and associated alternatives)

Scenario for Ecosystem Services Prioritisation

Stack 0 | Variable	**Value**
Name for my policy option	**EcoSer**
Weighting for realised/potential ES (fraction)	3.57143
Weighting for biodiversity (fraction)	0.357143
Weighting for conservation priority (fraction)	0.357143
Weighting for pressure (fraction)	0.357143
Weighting for threat (fraction)	0.357143
where	Study area (Hydrosheds)
is	>=
this value:	0
Show policy option	Show baseline and scenario

Reset to baseline run

Scenario for Conservation Prioritisation

Stack 0 | Variable	**Value**
Name for my policy option	**Cons**
Weighting for realised/potential ES (fraction)	0.217391
Weighting for biodiversity (fraction)	2.17391
Weighting for conservation priority (fraction)	2.17391
Weighting for pressure (fraction)	0.217391
Weighting for threat (fraction)	0.217391
where	Study area (Hydrosheds)
is	>=
this value:	0
Show policy option	Show baseline and scenario

Reset to baseline run

Scenario for Pressure and Threat Prioritisation

Stack 0 | Variable	**Value**
Name for my policy option	**PresThre**
Weighting for realised/potential ES (fraction)	0.217391
Weighting for biodiversity (fraction)	0.217391
Weighting for conservation priority (fraction)	0.217391
Weighting for pressure (fraction)	2.17391
Weighting for threat (fraction)	2.17391
where	Study area (Hydrosheds)
is	>=
this value:	0
Show policy option	Show baseline and scenario

Reset to baseline run

APPENDIX G

LIST OF PARAMETERS USED BY WATERWORLD POLICY SUPPORT TOOL, PROVIDED BY THE SIMTERRA DATABASE, EXTRACTED FROM THE POLICY SUPPORT SYSTEM (www.policysupport.org/waterworld)

Module and map name	**Layer name**	page 1 of 4
37, ueatmp4 (map)	Air temperature April	
41, ueatmp8 (map)	Air temperature August	
34, ueatmp12 (map)	Air temperature December	
35, ueatmp2 (map)	Air temperature February	
31, ueatmp1 (map)	Air temperature January	
40, ueatmp7 (map)	Air temperature July	
39, ueatmp6 (map)	Air temperature June	
36, ueatmp3 (map)	Air temperature March	
38, ueatmp5 (map)	Air temperature May	
33, ueatmp11 (map)	Air temperature November	
32, ueatmp10 (map)	Air temperature October	
42, ueatmp9 (map)	Air temperature September	
247, watb_wc (map)	Annual water balance (MODIS-WorldClim)	
8, blwind4 (map)	Boundary layer wind direction April	
12, blwind8 (map)	Boundary layer wind direction August	
5, blwind12 (map)	Boundary layer wind direction December	
6, blwind2 (map)	Boundary layer wind direction February	
2, blwind1 (map)	Boundary layer wind direction January	
11, blwind7 (map)	Boundary layer wind direction July	
10, blwind6 (map)	Boundary layer wind direction June	
7, blwind3 (map)	Boundary layer wind direction March	
9, blwind5 (map)	Boundary layer wind direction May	
4, blwind11 (map)	Boundary layer wind direction November	
3, blwind10 (map)	Boundary layer wind direction October	
13, blwind9 (map)	Boundary layer wind direction September	
216, cellarea (map)	Cell area	
117, modiscIddjf (map)	Cloud frequency (DJF)	
118, modiscldjja (map)	Cloud frequency (JJA)	
119, modiscldmam (map)	Cloud frequency (MAM)	
120, modiscldson (map)	Cloud frequency (SON)	
134, mcloud0-6 (map)	Cloud frequency 00:00-06:00 hrs	
137, mcloud6-12 (map)	Cloud frequency 06:00-12:00 hrs	
135, mcloud12-18 (map)	Cloud frequency 12:00-18:00 hrs	
136, mcloud18-24 (map)	Cloud frequency 18:00-24:00 hrs	
128, mcloud4 (map)	Cloud frequency April	
132, mcloud8 (map)	Cloud frequency August	

Module and map name	Layer name	page 2 of 4
125, mcloud12 (map)	Cloud frequency December	
126, mcloud2 (map)	Cloud frequency February	
122, mcloud1 (map)	Cloud frequency January	
131, mcloud7 (map)	Cloud frequency July	
130, mcloud6 (map)	Cloud frequency June	
127, mcloud3 (map)	Cloud frequency March	
129, mcloud5 (map)	Cloud frequency May	
124, mcloud11 (map)	Cloud frequency November	
123, mcloud10 (map)	Cloud frequency October	
133, mcloud9 (map)	Cloud frequency September	
159, vcfbare2000 (map)#	Cover of bare ground (Landsat)	
156, vcfbare2000 (map)#	Cover of bare ground (MODIS 2000)	
153, vcfbare2000 (map)	Cover of bare ground (MODIS 2010)	
160, vcfherb2000 (map)#	Cover of herb-covered ground (Landsat)	
154, vcfherb2000 (map)	Cover of herb-covered ground (MODIS)	
157, vcfherb2000 (map)#	Cover of herb-covered ground (MODIS)	
161, vcftree2000 (map)#	Cover of tree-covered ground (Landsat)	
155, vcftree2000 (map)	Cover of tree-covered ground (MODIS)	
158, vcftree2000 (map)#	Cover of tree-covered ground (MODIS)	
248, cropdisc (map)	Cropland (MODIS)	
209, crop2000 (map)	Croplands (2000)	
180, wcdtr4 (map)	Daily temperature range April	
184, wcdtr8 (map)	Daily temperature range August	
177, wcdtr12 (map)	Daily temperature range December	
178, wcdtr2 (map)	Daily temperature range February	
174, wcdtr1 (map)	Daily temperature range January	
183, wcdtr7 (map)	Daily temperature range July	
182, wcdtr6 (map)	Daily temperature range June	
179, wcdtr3 (map)	Daily temperature range March	
181, wcdtr5 (map)	Daily temperature range May	
176, wcdtr11 (map)	Daily temperature range November	
175, wcdtr10 (map)	Daily temperature range October	
185, wcdtr9 (map)	Daily temperature range September	
211, damid1k (map)	Dams	
29, hysh1kdem (map)	Elevation (Hydrosheds)	
269, glacier_we (map)	Glacier water equivalent (mm)	
224, grandkm2 (map)	GRanD reservoir area	
225, grand_id (map)	GRanD reservoir ID	
218, lake_ids (map)	Lakes	
152, lddhysh1k (map)	Local drainage direction (Hydrosheds)	
275, man_graz2005 (map)	Managed grazers (2005)	
121, mcloud (map)	Mean annual cloud frequency	

Module and map name	Layer name	page 3 of 4
74, wcprec4 (map)	Mean monthly precipitation April	
78, wcprec8 (map)	Mean monthly precipitation August	
71, wcprec12 (map)	Mean monthly precipitation December	
72, wcprec2 (map)	Mean monthly precipitation February	
68, wcprec1 (map)	Mean monthly precipitation Jan-Dec	
77, wcprec7 (map)	Mean monthly precipitation July	
76, wcprec6 (map)	Mean monthly precipitation June	
73, wcprec3 (map)	Mean monthly precipitation March	
75, wcprec5 (map)	Mean monthly precipitation May	
70, wcprec11 (map)	Mean monthly precipitation November	
69, wcprec10 (map)	Mean monthly precipitation October	
79, wcprec9 (map)	Mean monthly precipitation September	
99, wctmean4 (map)	Mean monthly temperature April	
103, wctmean8 (map)	Mean monthly temperature August	
96, wctmean12 (map)	Mean monthly temperature December	
97, wctmean2 (map)	Mean monthly temperature February	
93, wctmean1 (map)	Mean monthly temperature Jan-Dec	
102, wctmean7 (map)	Mean monthly temperature July	
101, wctmean6 (map)	Mean monthly temperature June	
98, wctmean3 (map)	Mean monthly temperature March	
100, wctmean5 (map)	Mean monthly temperature May	
95, wctmean11 (map)	Mean monthly temperature November	
94, wctmean10 (map)	Mean monthly temperature October	
104, wctmean9 (map)	Mean monthly temperature September	
20, gmslp4 (map)	Mean sea level pressure April	
24, gmslp8 (map)	Mean sea level pressure August	
17, gmslp12 (map)	Mean sea level pressure December	
18, gmslp2 (map)	Mean sea level pressure February	
14, gmslp1 (map)	Mean sea level pressure January	
23, gmslp7 (map)	Mean sea level pressure July	
22, gmslp6 (map)	Mean sea level pressure June	
19, gmslp3 (map)	Mean sea level pressure March	
21, gmslp5 (map)	Mean sea level pressure May	
16, gmslp11 (map)	Mean sea level pressure November	
15, gmslp10 (map)	Mean sea level pressure October	
25, gmslp9 (map)	Mean sea level pressure September	
206, initial_swe (map)	Mean snow water equivalent	
m_concess (map)	Mining concessions	
223, water_mask (map)	MODIS water mask	
og_concess (map)	Oil and gas concessions	
210, past2000 (map)	Pastures (2000)	
215, pov_pc (map)	Percentage of population considered poor	

Module and map name	Layer name	page 4 of 4
201, popct_landsc (map)	Population (Landscan)	
252, sres_p_2025 (map)	Population projection (SRES B2)	
253, sres_p_1990 (map)	Population projection (SRES B2)	
207, all_mines1k (map)	Presence of mines	
208, oilandgas1k (map)	Presence of oil and gas wells	
30, wdpa (map)	Protected areas (UNEP-WCMC WCPA) 2012	
61, uearh4 (map)	Relative Humidity April	
65, uearh8 (map)	Relative Humidity August	
58, uearh12 (map)	Relative Humidity December	
59, uearh2 (map)	Relative Humidity February	
55, uearh1 (map)	Relative Humidity January	
64, uearh7 (map)	Relative Humidity July	
63, uearh6 (map)	Relative Humidity June	
60, uearh3 (map)	Relative Humidity March	
62, uearh5 (map)	Relative Humidity May	
57, uearh11 (map)	Relative Humidity November	
56, uearh10 (map)	Relative Humidity October	
66, uearh9 (map)	Relative Humidity September	
187, roads1k (map)	Roads (GAUL)	
151, clone (map)	Study area (Hydrosheds)	
80, sumrain (map)	Total annual precipitation	
205, murban_500 (map)	Urban Areas	
226, swbd1k (map)	Water bodies (SWBD)	
217, wetlands (map)	Wetlands including lakes, rivers and reservoirs	
276, wildgr_2005 (map)	Wildland grazers headcount (2005)	
49, ueawnd4 (map)	Wind speed April	
53, ueawnd8 (map)	Wind speed August	
46, ueawnd12 (map)	Wind speed December	
47, ueawnd2 (map)	Wind speed February	
43, ueawnd1 (map)	Wind speed January	
52, ueawnd7 (map)	Wind speed July	
51, ueawnd6 (map)	Wind speed June	
48, ueawnd3 (map)	Wind speed March	
50, ueawnd5 (map)	Wind speed May	
45, ueawnd11 (map)	Wind speed November	
44, ueawnd10 (map)	Wind speed October	
54, ueawnd9 (map)	Wind speed September	

APPENDIX H

WATERWORLD/AGUAANDES MODEL DOCUMENTATION

VERSION 1 MODULES

This section describes the science, equations and assumptions behind the modules and submodules used. Version 1 of AguAAndes/Waterworld is a sophisticated model of spatial water balance which has been developed for data poor and spatially complex and heterogeneous environments. The model includes modules for distribution of rainfall through interaction with wind, occult precipitation through fog inputs, solar radiation receipt, potential and actual evapotranspiration on the basis of climate and vegetation cover, water balance and its cumulation downstream as runoff. There is also a simple model for soil erosion. The model requires some 140 inputs maps (all of which are provided with the system, globally) and calculates monthly and annual hydrological variable including water balance, runoff and soil erosion for a baseline representing year 2000 land cover and mean 1950-2000 climate. Users can run scenarios for climate change and land use change and examine the impact of these on hydrological ecosystem services including water quality and seasonality. Given the lack of global data on groundwater resources AguAAndes/Waterworld does not simulate subsurface hydrological processes associated with flows in soil and groundwater.

MODULE: HYDROLOGY

SUBMODULE: Atmosphere

Surface area
True surface areas (as opposed to planimetric areas) are calculated with the triangle method (Jenness, 2004). These are important for the accurate representation of surface area in montane environments. True surface areas can be 1.3 times the planimetric surface area for very steep rugged slopes.

Vegetation
Tree, herb and bare percentages from MODIS VCF are converted to fractions

Timesteps
The model iterates between four diurnal and 12 mensual timesteps (4 in each month) for a total of 48 timesteps for a complete run.

Input climate data
Key assumption : Winds bend around topography, taking the path of least resistance. It is sufficient to model these changes in direction without accounting for concentration (funnelling effects)

Wind directions are read and converted to the appropriate topographically affected wind direction by reading the appropriate wind direction file. Based on this wind direction, the appropriate TOPEX value is read from the topex files. Note that the wind direction file BLWind mis the directions that wind is going to whereas in the delivery model windspeeds are specified as directions that wind is coming from. Relative humidity, temperature, diurnal temperature range, wind speed precipitation and extraterrestrial solar radiation are read from the appropriate files.

Input cloud cover data for time of day and season
Key assumption : The MODIS data represents well the pattern of atmospheric cloud, where atmospheric cloud has formed and terrain level conditions are condensing (i.e. above the cloud

base), this cloud is likely to be present at ground level. MODIS derived cloud cover is read with the overall annual average value modified by seasonal and diurnal correction factors.

Temperature, dewpoint and liquid water content
Key assumption: Cloud liquid water content is proportional to absolute atmospheric humidity.
Temperature is modified according to the diurnal temperature range as follows:

```
Tmp=if(Hour eq 1 then Tmp-(0.25*DiurnalTRange) else
        if(Hour eq 2 then Tmp else
        if(Hour eq 3 then Tmp+(0.25*DiurnalTRange) else
        if(Hour eq 4 then Tmp
                ))))
```

Dewpoint and vapour pressure are calculated according to:

es=exp(26.66082-0.0091379024*(Tmp+273.15)-(6106.396/(Tmp+273.15)))
where
Tmp = temperature (C)
Es = saturated vapour pressure (mb)
RH = relative humidity (%)
E = vapour pressure (mb)

Air density and absolute humidity are calculated as:
AirDensity=(MSLP*100)/((Tmp+273.15)*287)
Where
AirDensity = kg/m3

whereby LWC varies linearly with AH under the assumption that the maximum AH observed at any one time is equivalent to the usually observed maximum LWC (0.0002 kg m3). Such a simplification is necessary because conversion of AH to LWC is complex depending on cloud condensation nuclei and cloud physics.

Dewpoint is calculated as:

btemp=26.66082-ln(e);
Td=((btemp-sqrt((btemp**2)-223.1986))/0.0182758048)-273.15;#dewpoint, C
where
Td = Celsius

Lifting condensation level
This means that the lifting condensation level (LCL) becomes
lcl=(1/(((Newtemp-Td)/223.15)+1)**3.5)*MSLP
lcl=max((44.3308-4.94654*((lcl*100)**0.190263))*1000,0)

Where
Newtemp = ground temperature (C)
The first part of Equation 10 produces the LCL in mb and the second part in masl

MSLP = mean sea level pressure (mb)
Liquid water content is distributed rather simplistically as :
LWC=(AH/mapmaximum(AH))*0.0002

SUBMODULE: Precipitation

Ground level cloud (fog) occurrence
Fog occurs where the ground altitude is greater than the LCL:

fog=scalar(Dem gt lcl)
where:
Dem = elevation (m)

Fog settling
Key assumption : That fog settling occurs under calm conditions and upwards fog turbulent diffusion is limited compared with this downward flux. Fog settling velocity is calculated according to Stokes Law based on the mean particle size for fog.

FogSettlingVel=(980*((7.5/10000)**2)*(1-0.0013))/(18*0.000185)

where 7.5 = fog droplet size in um

Forest edges
Key assumption : That forest edges are important and can be respresented as catching surfaces. That, as in the Chiquito, there is a random directionality of forest edges.
Forest is given an one sided LAI=3 and pasture LAI=2
Forest edges are calculated according to the tree fractional cover as :

forestedgefrac=-3E-05*Tree**2 + 0.0036*Tree
forestedgelenm=forestedgefrac*((CellSize*CellSize)/(25*25))*100
emergentedgelenm=(0.05*TreeFrac)*((CellSize*CellSize)/(25*25))*100
forestedgelenfacingm=(forestedgelenm/4)
emergentedgelenfacingm=(emergentedgelenm/4)

So, that the empirical equation derived from Figure 59 (Mulligan and Burke, 2005) provides the fractional forest edge length on the basis of tree fractional cover, this is converted to an actual length based on the cellsize of the grid compared with the original landsat grid. The fraction of exposed emergent trees is calculated as a 5% fractional of the area covered by tree. The division by four accounts for the fact that only one edge of a grid cell will face a wind from a particular direction.

Sedimentation surface area
Key assumption : That the whole unshaded (one sided) leaf surface area is available for sedimentation (deposition)

The surface area available for fog deposition (sedimentation) is calculated as:
ForestTrappingSfcArea=(1-(exp((-0.7*0.3*10))));#m/m*ForestLAI
PastureTrappingSfcArea=(1-(exp((-0.7*6*0.5))));#m/m*PastureLAI
DepositionFrac=(TreeFrac*ForestTrappingSfcArea*ForestLAI)+((1-TreeFrac)*PastureTrappingSfcArea*PastureLAI)

Fractional trapping areas for forest and pasture are calculated first (on the basis of leaf self shading). These are then multiplied by the fractional covers of tree and pasture for the grid cell and the available LAI.

Wind speeds modified for exposure:
Key assumption : The empirical parameters determined by Ruel (from wind tunnel studies) are representative. Exposure can be measured effectively from a DEM. Wind speeds are now modified for local wind direction dependent exposure using an approach modified from Ruel et al. (2002):

TanRainfallInclination=if(Prec gt 0 then windspd/DropTermVeloc else 0)
WindSlopeCorrectionfactor=if(Prec gt 0 then 1+Grad*TanRainfallInclination*cos(AspectDeg-WindDirDeg) else 0)
WindSlopeCorrectionfactor=max(WindSlopeCorrectionfactor,0)
Prec=Prec*WindSlopeCorrectionfactor
where:
Prec = monthly precipitation (mm)
Grad = slope gradient

AspectDeg = slope aspect (o)
WindDirDeg = wind direction (o)

Impaction fluxes
Key assumption : The windspeed reductions within forest and rough pasture measured at the FIESTA sites are generally representative

Fluxes of fog available for impaction are now calculated. The model has no spatial memory or budgeting of fog so fog passing through a forest is not necessary depleted along the flowpath – rather the model assumes that there is limitless availability of fog from the near surface atmosphere (when and where fog is present) thus no budget of atmospheric moisture is maintained. Impaction fluxes are calculated as:

WindFlux=(windspd*3600)*emergentedgelenfacingm*1.5
EmergentImpactionFlux=(LWC*WindFlux)

Wind speed at the grid scale is assumed unaffected by passing through occasional emergents. 1.5 is the average height of emergents above the surrounding canopy (1.5m).

Finally the amount of water passing pasture is calculated using the correction for observed wind speeds at pasture heights and the height of pasture assumed to be 0.5 m. A fog inclination angle for fog inputs over forest and pasture is calculated, based on their respective wind speeds. A vertical flux is calculated as the fog settling velocity over the whole cell surface area (rather than any vertical catching surfaces). The proportion of fog inputs that are deposited rather than impacted depends upon the cosine of the fog inclination angle over grassland and forest fractions.

WindFlux=(windspd*0.5030*3600)*(1-TreeFrac)*CellSize*0.5
GrassImpactionFlux=(LWC*WindFlux)
ForestFogInclinationAngle=scalar(atan((windspd*0.6053)/FogSettlingVel))
PastureFogInclinationAngle=scalar(atan((windspd*0.5030)/FogSettlingVel))
GravityFlux=(FogSettlingVel*3600)*Celltruearea
DeposProportion=((cos(ForestFogInclinationAngle))*TreeFrac)+
cos(PastureFogInclinationAngle))*(1-TreeFrac))
ImpactionProportion=1-DeposProportion

Vegetation areas for fog interception
Key assumption : Fog impaction occurs to all non shaded leaves according to the geometrical relationships between the angle of incoming fog (wind speed dependent) and the leaf area. Impaction only occurs on windward forest edges whereas fog passes over forest canopies or falls as sedimentation on leeward (topographically sheltered) forests.
Next the actual intercepting area of vegetation for fog is calculated because this will be combined with the previously calculated fog fluxes in order to calculate the fog interception. Surface areas for interception depend upon the leaf area density of the vegetation and the angle of incoming fog relative to leaves. The equations are:

ForestTrappingSfcArea=(1-(exp((-0.7*0.3*TreeFrac)/cos(ForestFogInclinationAngle))))
PastureTrappingSfcArea=(1-(exp((-0.7*6*(1-TreeFrac))/cos(PastureFogInclinationAngle))))
ImpactionFrac=(AirRising*ForestTrappingSfcArea)
ImpactionFlux=(EmergentImpactionFlux+EdgeImpactionFlux+GrassImpactionFlux)
SettlingFlux=LWC*GravityFlux

First the forest trapping surface area is calculated as the self shaded area of leaves exposed to fog droplets arriving at a particular angle (for the tree fraction of the cell). Pasture trapping surface area is calculated in a similar way (also according to pasture leaf area density and observed wind speeds). The impaction fraction is the fraction of the total potential impaction fluxes (to emergents, to edges and to grassland) that is trapped and so depends on the calculated forest trapping surface area. Importantly impaction only occurs in the model when air is rising because the model assumes that air flows close to the ground when moving uphill (usually in windward exposed) but above the ground in the leeward, more sheltered situations slopes, the parameter air rising is true for situation where upwind elevations are greater than the downwind cell.

Ratio of impaction to sedimentation
Key assumption: the balance between impaction and deposition depends upon the fluxes of water, the tendency towards lateral or vertical flow and the intercepting= areas for horizontal and vertical fluxes.

The proportional flux that will be deposited compared with that that will be impacted is calculated as:

DeposInterc=fog*(SettlingFlux*DeposProportion)*DepositionFrac;#kg/hr/cell total checked
ImpactionInterc=fog*(ImpactionFlux*ImpactionProportion)*ImpactionFrac

where the 'flux' is the volume of water passing by the representative surface area, the 'frac' is the fraction of that surface area that will intercept fog and the 'proportion' is the proportion of the flux that is horizontal and vertical (dependent of the balance between local horizontal wind speed and settling velocity).The parameter 'fog' denotes areas above the LCL for that timestep so where there is no fog there will be no fog flux. The units of FogInterc, DeposInterc and ImpactionInterc are kg/m2/hr. They are converted to mm/hr and multiplied by the cloud frequency to take account of those periods where the site may be above the LCL but no cloud generation has occurred:

FogIntmm=(FogInterc/Celltruearea)*(CloudFreqFrac)

Monthly total fluxes are the cumulation of the four monthly diurnal; fluxes and the 144 simulation hours that they represent:

Fogtotalmm.map=Fogtotalmm.map+(FogIntmm*6*30)

SUBMODULE: Evapotranspiration

Radiation receipt and correction for cloud and fog
Key assumption : The radiation reductions observed under cloud and fog at the FIESTA sites (Mulligan and Burke, 2005) are representative for other sites also.
Extra terrestrial radiation receipts are now converted to ground level radiation receipts by correction for dimming due to the presence cloud and fog using:

TransmissionLoss=if(fog eq 1 then (CloudFreqFrac*0.678)+((1-CloudFreqFrac)*-0.143) else (CloudFreqFrac*0.525)+((1-CloudFreqFrac)*-0.143))
SolarMJ=SolarMJ*(1-TransmissionLoss)

The empirical parameters for the effect of fog and cloud on radiation receipts were taken from the analysis of the hourly radiation dataset for the pasture site. In particular the measured radiation was compared with modelled extraterrestrial radiation for a the 1m pasture site pixel in which the weather station sits (Mulligan and Burke, 2005). The difference between modelled extraterrestrial and received land surface radiation by hour is a function of the transmission losses by cloud and fog. Thus these transmission losses were grouped according to those periods where the pasture site fog gauges were recording fog and those when they were not. This enabled the calculation of a mean transmission loss under cloudy conditions (no fog but Rmeas<<Rmodel) and foggy conditions (fog present and Rmeas<<Rmodel). Data were also analysed for clear conditions because the station recorded slightly lower values than the modelled values possibly because of more humid atmosphere above the station than parameterised in the atmospheric transmission component of the solar radiation model.

Net radiation

Key assumption : The solar to net radiation conversion functions measured under forest and grassland are representative for larger areas and other covers of similar density.

SolarWm=(SolarMJ*1000000)/(SecondsInMonth/2)
NetMap=((Tree/100)*(-27.9+(0.90*SolarWm)))
NetMap=NetMap+((1-(Tree/100))*(-27.5+(0.8*SolarWm)))

Again, the empirical constants for the simple linear regression of net with solar radiation for sensors above a forest and a pasture cover.

Intercepted energy fractions
Key assumption: That evapotranspiration is effectively modelled at this coarse spatial and temporal scale from consideration of energy availablility and atmospheric demand for water only. Leaf area is sufficient to represent plant processes and aerodynamic resistances can safely be ignored.

For simplicity and parsimony the model does not account for stomatal behaviour but rather defines the evapotranspiration differences between forest and pasture to be a function of the radiation intercepted by the canopy since this is the driver of both transpiration and wet canopy evaporation.

ExpLAI=(1-exp(-0.7*max(1,ForestLAI)))
EtFrac=TreeFrac*ExpLAI
ExpLAI=(1-exp(-0.7*max(1,PastureLAI)))
EtFrac=EtFrac+((1-(TreeFrac+BareFrac))*ExpLAI)

Thus the overall intercepted energy for ET is the sum of energy intercepted by tree leaves and by pasture in the grid cell.

Evapo-transpiration
Key assumption: Water availability is less significant in determining evapotranspiration than energy available.
Evapo-transpiration is calculated on the basis of the energy available (the net radiation received) and the surface area available for transpiration and wet canopy evaporation. Because of the time and space scales used surface, soil and wet canopy water balances were not possible so a water availability term could not be added to the model. Since available surface area (LAI) is a good surrogate for the availability of water through transpiring stomata or wet canopy evaporation, this was used here.

The equations are:

Ea=(611*exp((17.27*Newtemp)/(273.15+Newtemp)))/1000
SlopeSatCurveK=(4098*Ea)/sqr(273.15+Newtemp)
PotEvap=(SlopeSatCurveK/(SlopeSatCurveK+0.066))*NetMap
PotEvap=PotEvap*(60*60/1000000)
PotEvap=if(PotEvap gt 0 then (PotEvap/2.45) else 0)

ActEvap=if(PotEvap gt 0 then PotEvap*EtFrac else 0)

where:
Newtemp = air temperature (C)
Ea = vapour pressure (KPa)
SlopeSatCurveK= slope of the saturation vapour pressure curve (KPaC)
NetMap = Net radiation receipt (W/m2)
2.45 = latent heat of vapourisation of water (MJ/kg)

Thus evaporation is calculated on the basis of available energy and atmospheric demand to give potential evaporation and this is then combined with the non self shaded surface area available for the interception of radiation/evaporation of water to give something closer to actual evaporation, which is responsive to vegetation type and cover as well as climate conditions.

SUBMODULE: Water Balance

Water balance calculation
Key assumption : at these time and space scales losses to canopy, soil and groundwater are much less significant than the fluxes of rainfall and evapotranspiration. Precipitation is converted to mm/hr and the budget is calculated as:

Precmmh=Prec/(24*30)
Budget=((Precmmh+FogIntmm)-ActEvap))

VERSION 2 MODULES

Version 2 of AguAAndes/WaterWorld is still in development and beta testing with a small group of users. It builds upon version 1 by adding components for soil transportation and deposition to the soil erosion equations of version 1. Version 2 also adds an energy balance based snow & ice module, some changes to the way evapotranspiration is handled and a module for the spatial distribution of water quality. As well as the climate and land use change scenarios and policy options available for application in version 1, version 2 also incorporates modules for understanding the impact of land and water management interventions including bench terraces, fanya juu/bari terracing, check dams and existing or new reservoir dams.

MODULE: SOIL EROSION, DEPOSITION AND TRANSPORTATION

Full wash erosion, transportation and sedimentation model
Erosion according to Thornes (1990), E=kQmSne-0.07Vc
Transport capacity (Tc) according to stream power (Q, slope).
Sediment transport (S)=min (sediment from upstream+local erosion, P)
Sediment deposition where S>P

MODULE: SNOW AND ICE

Snow and ice model
Initial monthly snow cover according to MODIS
New snow is precipitation where T<<0
Full energy balance for snow accumulation and melting (after Walter et al. 2005)

MODULE: WATER QUALITY

Water quality (human footprint on water)
Calculates the % of water at a point which fell as rain on point and non-point potential sources of contamination upstream

MODULE: LAND AND WATER MANAGEMENT

Land uses - as well as land use being defined by the cover of Tree, Herb and Bare functional types, land use can also be defined by the land use type which can be one of Pasture, Cropland, Natural, Protected, Mining, Roads, Urban, Oil and gas. These types affect the water quality indices. The initial values for these covers are set according to available input maps but the covers can be changed with the land cover and change policy options.

Land use intensities - each land use has an associated intensity of use. This intensity is set to 1.0 by default for all land uses. The intensity value can be changed in order to reduce intensity (for example eco-efficient agricultural practices) or increase intensity (particularly destructive mining techniques).

APPENDIX I

WATERWORLD RUNS FOR BASELINE AND SCENARIOS WITHIN THE PSS

(www.policysupport.org/waterworld)

Here is a list of previous **baseline** runs of type **tiled/1-square-km** and origin **leozurita_gmail.com**.

SimTerra tile number: __9__11.corr.map.gz
Baseline run: col

username :	leozurita_gmail.com
runname :	col
model_version :	2.[.91dev]
runtype :	tiled/1-square-km
bbox_north :	10.0
bbox_south :	0.0
bbox_west :	-80.0
bbox_east :	-70.0
date_created :	(2014, 2, 25)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	m_concess
current_zoi :	ogconcesszip

Centre coordinates: 5.0,-75.0

Choose this baseline
Delete this baseline (and associated alternatives)

Alternatives for col:

View run details	Choose run	Delete run
mining55	Choose this run	Delete this run

SimTerra tile number: __10__11.corr.map.gz
Baseline run: ec

username :	leozurita_gmail.com
runname :	ec
model_version :	2.[.91dev]
runtype :	tiled/1-square-km
bbox_north :	-0.0
bbox_south :	-10.0
bbox_west :	-80.0
bbox_east :	-70.0
date_created :	(2014, 2, 27)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	
current_zoi :	ogconcesszip

Centre coordinates: -5.0,-75.0

Choose this baseline
Delete this baseline (and associated alternatives)

Alternatives for ec:

View run details	Choose run	Delete run
oilgas	Choose this run	Delete this run

Here is a list of previous **baseline** runs of type **tiled/1-hectare** and origin **leozurita_gmail.com**.

SimTerra tile number: _21_13_4_5.map.gz
Baseline run: tiputini

username :	leozurita_gmail.com
runname :	tiputini
model_version :	2.[.91dev]
runtype :	tiled/1-hectare
bbox_north :	-0.0
bbox_south :	-1.0
bbox_west :	-77.0
bbox_east :	-76.0
date_created :	(2014, 3, 7)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	0
current_moi :	popct_landsc
current_aois :	tipuB
current_zoi :	vcftree2000nonzeroszip

Centre coordinates: -0.5,-76.5

Choose this baseline
Delete this baseline (and associated alternatives)

Alternatives for tiputini:

View run details	Choose run	Delete run
oiltipu	Choose this run	Delete this run

SimTerra tile number: _21_12_5_5.map.gz
Baseline run: coello

username :	leozurita_gmail.com
runname :	coello
model_version :	2.[.91dev]
runtype :	tiled/1-hectare
bbox_north :	5.0
bbox_south :	4.0
bbox_west :	-76.0
bbox_east :	-75.0
date_created :	(2014, 2, 22)
run_period_begin :	
run_period_end :	
run_status :	completed
alternative :	baseline
database :	baseline
paramset :	default
data :	prepared
archive_status :	
write_timestep_maps :	1
current_moi :	popct_landsc
current_aois :	coellob
current_zoi :	mconcesszip

Centre coordinates: 4.5,-75.5

Choose this baseline
Delete this baseline (and associated alternatives)

Alternatives for coello:

View run details	Choose run	Delete run
coellomining	Choose this run	Delete this run